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HOW DECT-2020 SOLVES OFF-HIGHWAY VEHICLES MACHINE CONTROL CONNECTIVITY CHALLENGES

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ABSTRACT

Juho Pyykkönen: How DECT-2020 solves off-highway vehicles machine control connectivity challenges
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The purpose of this thesis was to investigate whether DECT-2020 network technology would be a suitable candidate for the industry's connectivity needs for future off-highway vehicle machine control applications. The off-highway vehicles in the scope of the thesis include many types of machinery for agriculture, construction sites, mining and port operations where the control at the current time is done by a human sitting in the cabin of the machine, but control is predicted to be moved into a remotely located control room in the near future, and after that to fully autonomous operation. The current networking solutions cannot meet the future higher data and latency requirements set by the applications. Therefore, the new DECT-2020 network technology is investigated as a potential candidate.

A brief history of DECT technologies is reviewed at the beginning of the thesis. After that, a discussion of the challenges of off-highway vehicle remote control is held and the use cases of the thesis are expressed. The summary of included use cases is:

- Building Information Model data transmission
- Remote control signalling
- Remote control video feed
- Safety signalling.

After the use case definition, common concepts of 5th generation networks, functional safety and mesh networking are introduced and the technical functionality of DECT-2020 is explained. After that, a comprehensive literature review is conducted to find the results done in existing DECT-2020 studies. In addition to the thesis, field measurements are conducted using preproduction DECT-2020 alpha-state devices. The DECT-2020's ability to meet the set use case requirements is investigated based on the literature review and conducted field tests.

At the time of writing the thesis, the DECT-2020 technology and commercial devices based on it were still under development and the used preproduction device could not show the full DECT-2020 performance. However, based on the literature review and field tests, the DECT-2020 seems promising and might be a strong candidate for the industry's off-highway vehicle remote control connectivity future needs. After this thesis, further investigation should be conducted into the reliability and mobility aspects of DECT-2020 to compare the DECT-2020 with other available network technologies for the final decision in choosing the proper network technology for the final use cases.

Keywords: DECT-2020, NR+, remote control, 5G

TIIVISTELMÄ

Juho Pyykkönen: Kuinka DECT-2020 ratkaisee tieliikenteen ulkopuolisten ajoneuvojen ohjauksen yhteyshaasteita
DI-työ
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Tämän opinnäytetyön tarkoituksena oli selvittää, olisiko DECT-2020 -verkkotekniikka sopiva ehdokas teollisuuden tarpeisiin off-highway -ajoneuvojen etäohjauksen käyttötapauksissa. Off-highway -ajoneuvot sisällytettynä tähän opinnäytetyöhön sisältävät erilaisia koneita, joita käytetään esimerkiksi maataloudessa, rakennustyömailla sekä kaivos- ja satamatoiminnassa. Tällä hetkellä näissä käyttötapauksissa koneiden ohjauksen hoitaa koneen ohjaamossa sijaitseva ihminen, mutta on ennustettu, että tulevaisuudessa koneiden ohjaus tapahtuu etänä sijaitsevasta valvomosta ja vielä myöhemmin täysin autonomisesti. Nykyiset verkkoratkaisut perustuivat radiolinkkeihin, jotka eivät täytä tulevaisuuden käyttötapausten tiedonsiirron kaista- ja viivevaatimuksia. Uusi DECT-2020 -teknologia on esitetty potentiaaliseksi kandidaatiksi ja sen soveltuvuutta käyttötapauksiin tutkitaan tässä opinnäytetyössä.

Opinnäytetyön alussa käydään läpi DECT-teknologioiden historia. Sen jälkeen tuodaan esiin off-highway -ajoneuvojen etäohjauksen haasteita ja määritetään käyttötapausten tiedonsiirron vaatimukset. Listaus työhön sisällytetyistä käyttötapauksista on listattu alle.

- Rakennustyön tietomallin siirto
- Etäohjauksen signalointi
- Etäohjauksen videodata
- Turvasignalointi.

Käyttökohteiden määrittelyn jälkeen käydään läpi yleisiä viidennen sukupolven verkkoteknologian, toiminnallisen turvallisuuden ja mesh-verkkoteknologian periaatteita sekä käydään läpi DECT-2020 tekniset ominaisuudet. Tämän jälkeen kattava kirjallisuuskatsaus on suoritettu olemassa olevien tutkimusten tulosten löytämiseksi DECT-2020 -teknologiasta. Lisäksi DECT-2020 sopivuutta asetettuihin käyttökohteisiin tutkitaan kirjallisuuskatsauksella olemassa oleviin tutkimuksiin ja julkaisuihin. Lisäksi opinnäytetyössä suoritettiin kenttämittauksia DECT-2020 esituotanto alpha-tason laitteistolla. DECT-2020 kykyä suoriutua asetetuista käyttötapausten vaatimuksista arvioidaan kirjallisuuskatsauksen tulosten sekä kenttämittausten tulosten perusteella.

Opinnäytetyötä kirjoitettaessa DECT-2020 -teknologia ja siihen perustuvat kaupalliset laitteet olivat vasta kehitteillä, eikä testauksissa käytetty esituotannon laitteisto kyennyt näyttämään täyttä DECT-2020 -teknologian suorituskykyä. Kuitenkin perustuen kirjallisuuskatsaukseen ja kenttämittauksiin, DECT-2020 näyttää lupaavalta ja saattaa olla vahva ehdokas teollisuuden off-highway -ajoneuvojen etäohjauksen tulevaisuuden tarpeisiin. Tämän opinnäytetyön jälkeen lisätutkimuksia DECT-2020:n suorituskyvystä luotettavuudesta ja mobiliteetista vertaamiseksi muihin verkkoteknologioihin täytyy vielä suorittaa lopullisen päätöksen tekemiseksi oikean verkkotekniikan valitsemiseksi lopulliseen käyttökohteeseen.

Avainsanat: DECT-2020, NR+, etäohjaus, 5G

PREFACE

This thesis has been done as a byproduct of two parallel partially Business Finland-funded projects Next Generation Mining and Project USWA. The work's end customer was Satel Oy and the work was conducted as a subcontract from Huld Oy, where I was working. Both Satel Oy and Huld Oy were present in the Next Generation Mining project and the Satel Oy was present in the Project USWA.

The work started at the end of the year 2022, and the initial plan for completion was summer 2023. Now writing this preface, I could say that we were able to stay on the original schedule quite well, even when there were a couple of interruptions to the work due to other projects.

I would like to thank the supervisors from both companies, especially Heikki Keränen, who worked as the main supervisor from the Satel and conducted the main steering task for the work. From Huld's side, I would like to thank Kalle Määttä who worked as a second supervisor, Vesa Vuorinen for being an encouraging foreman and Vladimir Kurdin for proofreading the thesis and giving technical feedback on it. I would like to thank the Tampere University professors Jukka Vanhala and Karri Palovuori for working as supervisors from the academic side.

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GLOSSARY OF ABBREVIATIONS

3GPP	3rd Generation Partnership Project
ACK	Acknowledgment
ARQ	Automatic Repeat Request
BCC	Broadcast control
BCCH	Broadcast Control Channel
BIM	Building Instruction Model
BSC	Beacon Scanning control
CCC	Connection configuration control
CCCH	Common Control Channel
CP-OFDM	Cyclic Prefix Orthogonal Frequency Division Multiplexing
CRC	Cyclic Redundancy Check
CVG	Convergence layer
DCCH	Dedicated Control Channel
DCH	Dedicated Channel
DECT	Digital Enhanced Cordless Telecommunications
DECT ULE	DECT Ultra Low Energy
DECT-2020 NR	DECT-2020 New Radio
DF	Data Field
DLC	Data Link Control
DLC-A	Data Link Control Automatic Repeat Request mode
DLC-S	Data Link Control Segmentation mode
DLC-T	Data Link Control Transparent mode
DRS	Demodulation Reference Signal
DTCH	Dedicated Traffic Channel
eMBB	enhanced Mobile Broadband
ETSI	European Telecommunications Standards Institute
FDMA	Frequency Division Multiple Access

FFT	Fast Fourier transform
FT	Fixed Termination point
GI	Guard Interval
GSD	General Station Description
GSM	Global System for Mobile communication
HARQ	Hybrid Automatic Repeat Request
HSPA	High-Speed Packet Access
IEC	International Electrotechnical Commission
IMT	International Mobile Telecommunications
IMT-2020	International Mobile Telecommunications-2020
IoT	Internet of Things
ISD	Inter-site distance
ISDN	Integrated Services Digital Network
ISO	International Organization for Standardization
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
Long RD ID	Long Radio Device ID
LOS	Line Of Sight
LPWAN	Low Power Wide Area Networks
LRC	Local radio control
LSB	Least significant bit
LTE	Long Term Evolution
LTE-M	Long-Term Evolution Machine Type Communication
M2M	Machine-to-machine communication
MAC	Medium access control
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input and Multiple-Output
mMTC	Massive Machine Type Communication
MSB	Most significant bit
MTCH	Multicast (Broadcast) Traffic Channel
NACK	Negative Acknowledgment
NB-IoT	Narrowband Internet of things

NG-DECT	New Generation DECT
NLOS	Non-Line Of Sight
NR+	New Radio Plus
PCC	Physical Control Channel
PCCH	Paging Control Channel
PCH/BCH	Paging and Broadcast Channel
PDC	Physical Data Channel
PER	Packet Error Rate
PHY	Physical layer
PL	Performance Level
PLR	Packet Loss Rate
PSK	Phase-shift keying
PSTN	Public Switched Telephone Network
PT	Portable Part
PTC	Paging Transmission Control
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RAC	Random Access Control
RACH	Random Access Channel
RD	Radio Device
SDO	Standards Developing Organization
SDU	Service Data Unit
Short RD ID	Short Radio Device ID
SIL	Safety Integrity Level
SIMO	Single-Input and Multiple-Outputs
SISO	Single-Input and Single-Output
SNR	Signal-to-noise ratio
STF	Synchronization Training Field
TBS	Transport Block Size
TC DECT	Technical Committee DECT
TCP	Transmission Control Protocol
TDD	Time Division Duplex

TDMA	Time Division Multiple Access
TTI	Transmission Time Interval
UART	Universal Asynchronous Receiver Transmitter
UPCS	Unlicensed Personal Communications Service
URLLC	Ultra Reliable and Low Latency Communication
VoIP	Voice over IP
VTT	Technical Research Centre of Finland

1. INTRODUCTION

The machines in applications like agriculture, mines, construction sites and port operation are defined in this thesis as off-highway vehicles. The common aspects of the machines are for example relatively slow speed, limited operational area, working outside asphalt roads and co-operation with other machines. At the current time, the machines are driven by a human operating inside the machine and controlling the machine directly using pedals, steering wheel, joysticks and buttons.

It is seen that in the future people are moved out of the machine's cabins to remotely located control rooms, where the operation of the machine can be controlled remotely out of the working area. Providing solutions to the communication between the remote control room and the machine is in Satel's interest, but with the current technology portfolio that Satel offers at the moment, the strict requirements for data throughput, latency, reliability and range are not met.

The DECT-2020 technology is developed by the European Telecommunications Standards Institute (ETSI) as a solution for local area wireless applications in massive Machine Type Communication (mMTC) and Ultra Reliable Low Latency Communication (URLLC) applications [12]. The ETSI is a non-profit organization consisting of many member organizations worldwide, such as research institutes, academia, public organizations and private companies [26]. The DECT-2020 is seen by Satel as a potential technology for the industry's use cases for off-highway vehicles. The technology is still under development and none of the commercial devices yet exist, but the first revisions of DECT-2020 standards have been published and a few studies and whitepapers have been released.

2. HISTORY OF DECT

Digital enhanced cordless telecommunications (DECT) is a radiocommunication technology developed and maintained by ETSI. The DECT was initially a multipurpose technology for audio applications in the 1990-century but was then developed further to support many different applications. [12]

Within the ETSI, there is a Technical Committee DECT (TC DECT) which is responsible for the development and maintenance of DECT standards. Today the DECT standards form two groups of standards of which one group is for "classic" DECT technology and the other for newer DECT-2020 NR. Most of the current development focuses on the new DECT-2020 NR technology, but the classic DECT standards are also maintained and improved. [12]

2.1 Classic DECT

The original "classic" DECT was developed in the 1990-century for short-range cordless communications, which focus was not limited to certain applications but can be used for many needs. The technology was initially developed as a European standard, but then spread to many other countries and has become widely used for cordless telephony applications. [5]

DECT commonly uses 1880 MHz to 1900 MHz frequency allocation in Europe, which is exclusive for DECT ensuring interference-free operation. Outside Europe frequency bands 1900 MHz to 1920 MHz and 1910 MHz to 1930 MHz are also used. In US, the band 1920 MHz to 1930 MHz is used, known as the Unlicensed Personal Communications Service (UPCS) band. [12]

The classic DECT was developed in the era of Public Switched Telephone Network (PSTN) and Integrated Service Digital Network (ISDN) and was made to be compatible with the standards and technologies used at that time [12]. DECT can be used for voice, data and networking applications and its range can reach up to 500 m [5]. It is widely used in cordless residential marked and in enterprise applications [5].

On the physical layer, the DECT operates in the 1880 MHz to 1900 MHz frequency range and splits it into ten channels with 1728 kHz guard bands. The standard operates in

Time Division Multiple Access (TDMA) and Time Divison Duplex (TDD) schemes, with one frame providing twelve duplex speed channels. [5]

The classic DECT uses a frame time of 10 ms, which consists of 24 slots. Supported symbol modulations are QPSK, 4-PSK, 8-PSK, 16-QAM and 64-QAM.[5]

2.2 New Generation DECT

New Generation DECT (NG-DECT) was published starting from 2007 and was a set of standards to improve the DECT for audio and data applications [3]. NG-DECT was implemented by keeping the backward compatibility for classic DECT and adding new application profiles to enable support for new products. [12].

The new features were published in the standards TS 102 527 parts 1-5, and included, for example, the following features:

- Better audio quality by implementing enhanced audio codecs with audio bandwidth of 150 Hz to 7 kHz and 16 kHz sampling rate [20],
- Improved packet-based data service supporting IP-protocol [21],
- Improved wide bandwidth speech support [22] and
- Light Data Services, adding support for over-the-air software upgrades for the devices, basic binary data transmission and limited HTTP browsing support [23].

The NG-DECT can be then seen as an evolution to the classic DECT standard as it adds new functionalities, but keeps the backward compatibility. The classic DECT was thus left untouched and permitted the classic DECT devices to continue their operation.

2.3 DECT Ultra Low Energy

DECT Ultra Low Energy (DECT ULE) was published in 2013 [24]. It was intended for low power, low data rate Machine-to-Machine type communication in applications such as sensor networks in home automation, security, monitoring, metering, healthcare and energy management [8]. The main principles of the technology were ultra-low energy consumption and wide coverage [12]. From the design perspective, the aim was for energy consumption to be lower than on the IEEE 802.11 and the range wider than 802.15 and/or Bluetooth Low Energy [12].

The base characteristics of DECT ULE are from classic DECT and it is designed to coexist with other DECT applications. The coexistence is taken into account in the standardization, and different generation of DECT devices can operate at the same spectrum in the same time. [12]

The DECT ULE utilizes a start topology and provides up to 70 meters of coverage indoors and 600 meters of coverage outdoors, with a maximum data rate of 1Mb/s. It does not provide mesh functionality. [8]

The DECT ULE can operate in two modes: synchronous mode, called "locked mode", and asynchronous mode, called "unlocked mode". In the synchronous mode, the device is configured to communicate with the base every x seconds, where x is configured with sleep time between 1-20 seconds. In the asynchronous mode, the sleep time can be from seconds to days. In the table 2.1, the expected battery times on devices running 2x AA alkaline cells can be seen. The data is provided by ETSI Forum [8].

Table 2.1. *Battery lifetime estimate on DECT ULE device running on 2x AA alkaline battery [8].*

Mode	Sleep time	Battery last
Asynchronous (unlocked)	5-6 mins	10 yrs
Asynchronous (unlocked)	2.5 mins	5 yrs
Synchronous (locked)	20 seconds	4 yrs

The DECT ULE specification was published in two phases. Phase 1 ETSI TS 102 939-1 was launched in 2013 and phase 2 ETSI TS 102 939-2 in 2015. [24][25]

2.4 DECT Evolution

DECT Evolution was an evolution program targeted to enhance DECT even further by implementing a number of technical improvements to the base DECT specification. The technology is still based on previous DECT standards, but new features are implemented especially for enhanced audio applications, such as increased bit rate, channel coding and latency reduction. [31]

Some of the new features in the DECT Evolution are [31]:

- Better support for High-Level Modulation and Modulation and Coding Schemes (MCS) to increase the data rate,
- New MAC structures for reduced delay handovers to change channels in highly occupied areas,
- Improved procedures for double simplex bearers to decrease latency and allow asymmetric connection and
- New LC3plus audio codec for voice services.

In the process of the improvements, the URLLC aspects of the DECT were enhanced as well. As the DECT by itself works in a dedicated 1.9 GHz frequency band, there are no similar overcrowding issues in, for example, a licence-free 2.4 GHz band which provides a good starting point for reliability. During the DECT Evolution, sub-frames within the 10 ms main-frames are introduced to enable smaller latency. As the main frame is still the same 10 ms as classic DECT, the cooperation with other DECT devices remains. [31]

2.5 DECT-2020

The DECT-2020, also called DECT-2020 New Radio (DECT-2020 NR) and New Radio Plus (NR+), is the newest generation standard to the DECT family. During the writing of this thesis, the publication of original standards were published in 2020 and the latest update to standards in early 2023, but no commercial products utilizing DECT-2020 exists yet.

The DECT-2020 is a technology designed for providing wireless technology for many use cases and applications. The radio interface is designed to be flexible and can be utilized in many applications, for example, wireless telephones, different audio applications, Internet-of-Things (IoT) applications and other consumer and professional applications. [15]

The DECT-2020 works on the same sub-6 GHz frequency range as the older DECT standards. The DECT-2020 is designed to fulfil the International Mobile Telecommunications-2020 (IMT-2020) requirements for URLLC and mMTC use cases and is developed to be a local area network that can be deployed anywhere without existing infrastructure. [15]

On the physical layer, the DECT-2020 utilizes Cyclic Prefix Orthogonal Frequency Division Multiplexing (CP-OFDM) as modulation. For multiple access Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) are used. The physical layer properties can be scaled with used numerologies, scaling the used subcarrier spacing, Cyclic Prefix length and Fast Fourier transform (FFT) size to optimize the utilization in different frequency bands, radio propagation situations and user requirements. The physical layer reliability is achieved with the use of Turbo Coding and Hybrid Automatic Repeat Request (HARQ). [15]

3. CHALLENGES ON OFF-HIGHWAY VEHICLES CONNECTIVITY

First of all, the term off-highway vehicle needs to be defined. In industry use cases, the term off-highway vehicle covers multiple types of machinery used in industry and construction sites. The machines targeted in this thesis are used in work environments, for example, construction sites, mines, port operations, airports, industrial areas, agriculture and railway depots to list some. The common aspects of the machines are, for example, big mass, relatively slow speeds and the ability to operate outside of asphalt roads. The machines are designed for specific applications that are restricted. At the moment, the machines need a driver in the cabin. Some practical examples of the machines in this scope are excavators, dump trucks, tractors, mining machines, harvesters and port cranes.

3.1 Usecases and requirements

At the current time, the machines are driven by a person sitting physically in the machines' cabin. In the long term, this has not been a viable option. People working in the same area with the machines require careful planning for the safety aspects in order to keep the workers safe. For example, people require good air quality and a suitable air temperature, which requires extra types of equipment for air ventilation in the working area which increases the total costs.

It has been seen in Satel Oy and related industries that the next evolution from the current state is to transfer people from the machines' cabins to remote locations from where the machines can be driven remotely using a video stream from the machine. However, the evolution happens gradually in small steps in time. One idea for future evolution is to split the development and requirements into three phases shown in figure 3.1. In the first stage, which could be said to be already around the corner, the sensor and process data from the machines will be increased, as new services accumulate which requires connectivity out of the machines. The sensor and process data are transferred between the machine and the backend and between the machine and another machine in the area. In the second stage, the process data stays but the people controlling the machines are moved out of the machine's cabin to the remote control room. In the third stage, the control of machines is migrated to fully autonomous operation, where people have only a supervisor and commander role. However, the split into three stages could be more of an ideology and in practice, the evolution is more gradual.

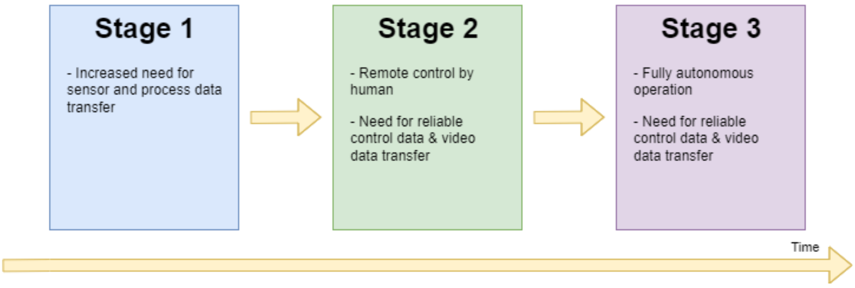


Figure 3.1. *Illustration of future requirements phases.*

In the first stage, the requirements for the connectivity can be called machine control data transmission or building instruction model (BIM) data transmission. In the construction industry, BIM is a technique where a digital 3D model of the construction work or the final building is available [6]. The BIM model can be saved to the machine during the construction work and then the machine knows what the expected output should be. The model can also include many types of supportive information and metadata of the construction site and work.

During the work, the machine knows the environment and updates the internal model of the construction state. The progress is transmitted to the backend systems, where the construction progress can be monitored.

In the initial phase, the initial BIM model needs to be transmitted to the machine. The model can be a couple of hundred megabytes in size, which requires high throughput to the connectivity. However, after the initial transfer is done, the possible updates to the model are smaller.

During the construction, the machine collects progress information. The progress information includes data, for example, the position of the machine's boom at a certain time. The progress information is sent periodically to the backend server and is smaller in size than the initial model.

The requirements for BIM transmission are shown in the table 3.1. The source used for the requirements is a personal interview with Antti Kolu, Novatron done on 25.5.2023. The most critical criterion is the throughput. During the initial BIM transmission, the required throughput is in the order of 100 Mbit/s. Later during the work progress information data transmission, the required throughput is loosened down to 2 Mbit/s. The data is file transmission and usually the transmission exists on top of another protocol such as Transmission Control Protocol (TCP), and the reliability and latency requirements are not that tight. The upper layer protocols are able to do required retransmissions if some minor packet loss occurs on the network. At the moment, the data update interval at the backend is enough of being the order of seconds, so the latency is not very critical either.

Table 3.1. *Building Information Model data transmission requirements.*

Throughput (Initial BIM transmission, downlink)	100 Mbit/s
Throughput (Work progress update, uplink)	2 Mbit/s
Latency	Order of seconds (not latency critical)
Range	1000 m
Mobility	40 km/h
Reliability	>98 %
Number of datalinks on the area	100

Giving more practical examples, the process data transfer can also happen between machines and only less frequent status reports are sent to the backend. A practical example in agriculture is a combine harvester and a tractor with a trailer, which can have a machine-to-machine connection between them. The combine harvester has a boom that supplies corn to the tractor's trailer. The trailer can then have a camera and/or sensors to determine that the corn is supplied in the proper position of the trailer for equal filling and indicates when the trailer is full. The tractor can then send that data to the combine harvester so the combine harvester can tune the boom's position. In this kind of machine-to-machine communication, the required range for mobility is tens of meters.

The area of interest is set to be at a maximum of 2 km in diameter where the machines are defined to move. For a machine to the backend system, we can imagine that there exists one base station in the centre of the area, so the length of the first hop radio link between the machine and the base station is a maximum of 1000 m. The backend system itself might be located at further distances behind another network or in the cloud, so in that sense, the upper limit of connectivity end-to-end range is not defined.

The requirements table 3.1 represents well the requirements for process data transmission. However, the actual process data in different applications is varying. The general process data applied to all industries are, for example, a machine's engine hours, operation times, fuel consumption, maintenance information and vehicle position. In the industry-specific ones, some examples are the number of logs from a harvester and the location of the logs in the forestry, the number of seeds sown to a field, the amount of pesticides used and pesticide coverage information in agriculture, the weight of transported ore in the mining industry and weight of a container, location of containers and fleet management in port operation.

In stage 2, the process data transfer is retained but remote control data is also added to communication. The remote control consists of two major types of data streams between the control centre and the machine, which have different requirements for connectivity, remote control signalling and remote control video feed.

Remote control signalling includes all the control signals that are used to control the machine. These types of signals are from the input from the controller's joystick to move the machine's scoop, and feedback from the machine scoop's sensors back to the control room. Based on Satel's earlier investigations into the industry and the end users, the set requirements for the use case are found and illustrated in the table 3.2. The source for throughput requirement is from [27], the source for maximum tolerable latency is based on field discussion of machine operators done by Satel, and the source of reliability requirements is from Process automation - remote control use case from [36]. The range comes from the own definition of restricting the operation area to the circle of radius of 1 km and the maximum practical amount of machines working on the same area is seen to be 100.

Table 3.2. *Requirements for off-highway vehicle - remote control by human.*

Throughput	3 Mbit/s
Latency	<300 ms
Range (machine to backend, first hop)	1000 m
Range (end-to-end)	No upper limit
Mobility	40 km/h
Reliability	>99,9999 %
Number of datalinks on the area	100

The video feed is the third use case from this set. It is basically the video from the machine's multiple cameras to the remote control room. Rather than control signalling, video reliability is not that critical and tolerates some packet drops to be still usable. The required throughput on the other hand is much higher and sets higher requirements for the network. The requirements are shown in the table 3.3

Based on the earlier field test measurements made by the University of Oulu, Satel Oy and Kaitotek Oy on [27] the control signalling and the used video feed can fit into a data rate of 3 Mbit/s. It still has to be mentioned that the actual video data rate depends heavily on the number of used cameras, their resolution, refresh rate and used codecs. For that reason, the lower limit can be just a couple of megabytes per second, whereas the upper limit can be tens of megabytes per second. The requirements for range, mobility and number of datalinks on the area are inherited from the previous use case.

Table 3.3. *Requirements for off-highway vehicle - video feed.*

Throughput	<2 Mbit/s - X x 10 Mbit/s
Latency	<40 ms
Range (machine-to-backend, first hop)	1000 m
Range (machine to machine)	50 m
Mobility	40 km/h
Reliability	>98 %
Number of datalinks on the area	100

The upper requirements are for the phase when human operators are controlling the machines, but remotely. Satel has observed that in related industries, that remote control is only a temporary solution before fully autonomous machines become more common. When the development reaches a fully autonomous state, the requirements for communication become even tighter. This is because people have a finite reaction time, which is relatively high compared to the upper requirements of the network, thus making the overall latency higher. Because of the people on the signal path, lowering the network latency further does not gain high benefit and, for example, there needs to be relatively high safety margins between the machines.

In the third stage, when the people are taken out of control and machines are driven autonomously by their own, the reaction times are much smaller compared to people. That makes it possible to narrow the safety marking between the machines and then increase the overall production efficiency, but with the cost of higher requirements for the communication. The new set of requirements for control signalling in case of autonomous operation is shown in table 3.4.

Table 3.4. *Requirements for off-highway vehicle - remote control autonomously.*

Throughput	3 Mbit/s
Latency	<10 ms
Range (machine-to-backend, first hop)	1000 m
Range (machine to machine)	50 m
Mobility	40 km/h
Reliability	>99,9999 %
Number of datalinks on the area	100

Based on the earlier field test measurements made by the University of Oulu, Satel Oy and Kaitotek Oy in the paper [27] the control signalling can fit into a data rate of 3 Mbit/s. The measured 3 Mbit/s also included the video feed used on the test, so the actual control signalling requires less than 3 Mbit/s. In the test, a delay of 30 ms was measured, which was too much for smooth autonomous operation. Based on that, the autonomous operation requires a shorter delay than 30 ms. [27]

The shown requirements set new challenges to the networks that need to be fulfilled. One problem is transmitting both latency-critical data and throughput-intense data on the same datalink while still maintaining the needs of both applications.

At the moment, the related off-highway vehicles include many safety functions. When the transformation to remote and autonomous drive happens, the urgency of safety functions increases. The safety functions can run as a dedicated system in isolation from the control function. On machines examples of varying safety functions are for example: stopping, emergency stop, propulsion, safety-rated reduced speed and steering [32]. Some of these or some other functions can be utilised as safety functions.

Different safety-related functions are run on off-highway vehicles. The functions are usually implemented on top of a functional safety protocol such as PROFIsafe, FF-SIS or SafetyNet which uses a black channel approach. The protocols are based on cyclic messages, which are sent periodically to carry data and determine whether the connection between nodes is up [39]. The interval of periodic messages is called cycle time and it determines the response time of the system, and then the delay of the safety signals to reach the destination. For example, in PROFIsafe has a parameter watchdog time that has a direct dependence on the machine's stopping distance [29].

Requirements for safety signalling can be seen in the table 3.5. The source for throughput requirement, latency and reliability are based on an internal discussion with Satel. Requirements for range, mobility and number of datalinks on the area inherit from previous use cases.

Table 3.5. *Requirements for off-highway vehicle - safety signalling.*

Throughput	5 Mbit/s
Latency	<32 ms
Range (machine-to-backend, first hop)	1000 m
Range (machine to machine)	50 m
Mobility	40 km/h
Reliability	>99,9999 %
Number of datalinks on the area	100

Overall, the off-highway machine control includes many types of data in different stages with different requirements. To fulfil the requirements, the used network technology needs to be flexible to meet all the requirements which set in a different area of the 5G triangle.

3.2 Environmental challenges

The environment where off-highway vehicles are used sets its own challenges to wireless communication. The environments on construction sites, mines, agricultural farms and ports are far away from ideal from a signal propagation perspective and thus create challenges for connectivity.

Taking into account, for example, construction sites, the location includes many different kinds of materials with varying wave propagation properties. The materials found on the construction sites can be, for example, concrete, reinforced steel, glass, wood and other physical structures like trees and scaffolds. The connectivity ranges can vary significantly depending on the construction site type, from a small house to a big airport or hospital construction. [13]

The second common industry for off-highway vehicles is mines and tunnel construction sites. Both utilized quite similar environments located under the surface quarried in the rock. The environment under the tunnels is extremely difficult for radio propagation. The air in the tunnels is hot and dusty. There is usually an effort to reduce the dust by spraying water on the floor of the tunnels, but that makes the air humid. Both dust and humidity affect radio propagation negatively. Dust scatters radio waves around the frequency of 1 GHz and humidity absorbs frequencies around 10 GHz. The tunnel network consists usually tunnels of several hundred meters, which makes the signal propagation Non-Line Of Sight (NLOS) type. The tunnels are also changing constantly and machines and workers are moving in the tunnels, so the environment is also dynamic in that sense. [7] [32]

In agriculture, remote distances and large areas are the biggest challenges to wireless communications at the moment. The fields in question can be very large in area and the fields are usually located in remote locations. [43]

In port operation, the obstacles around and dense networks cause challenges to the networking. The areas are usually heavily populated with different metal obstacles such as buildings, sea containers, cranes, lifts and other machinery.

3.3 Functional safety

Functional safety is a concept of safety functions on control systems meant to prevent accidents. The concepts and solutions for functional safety systems are declared precisely by different standard institutes such as International Electrotechnical Commission (IEC) and International Organization for Standardization (ISO). On the scope of functional safety, the system consists of input devices (e.g. sensors and pushbuttons), logic, and actuators (e.g. brake control, speed control or power cut-off circuit). The required safety function can be found during risk assessment, where sufficient safety function for risk is asserted. The requirements are categorized into Performance Levels (PL) on ISO 13849-1 standard. The PLs are levels from PL a to PL e, where the risk is categorized accordingly, and the corresponding safety function is designed to meet the set level. Other standards and acronyms also exist for risk categorizing and requirements. The standard IEC 61508 introduces the idea of Safety Integrity Levels (SIL). [32]

The Safety Integrity Levels are defined as four level levels: SIL 1, SIL 2, SIL3 and SIL 4. The higher the level, the more stringent the requirement. The SIL levels and their requirements are shown in table 3.6.

Table 3.6. *SIL-levels [41, s.7].*

Safety Integrity Level	High demand rate (dangerous failures/hr)	Low demand rate (probability of failure on demand)
4	$\geq 10^-9$ to $< 10^-8$	$\geq 10^-5$ to $< 10^-4$
3	$\geq 10^-8$ to $< 10^-7$	$\geq 10^-4$ to $< 10^-3$
2	$\geq 10^-7$ to $< 10^-6$	$\geq 10^-3$ to $< 10^-2$
1	$\geq 10^-6$ to $< 10^-5$	$\geq 10^-2$ to $< 10^-1$

The reason for splitting the requirements into high-demand and low-demand rates is the great difference between the rate of the probable hazard occurring after the occurred failure of the system. For example, car brakes can be classified as high demand because the use interval of the brakes is fast and possible failure on the brakes leads to a hazard in high probability. On the other hand, the car airbag system can be classified as a low demand rate, as the demand for the system is infrequent, and a single failure on the system might not lead to a direct hazard. [41]

3.3.1 Communication and functional safety

Functional safety is defined strictly by different standards as is the communication used in functional safety. Many IEC standards exist regarding functional safety. The IEC 61508 is the base functional safety standard, which defines the basic principles and, for example, the SIL levels. The IEC 62061 defines the functional safety in machinery, which includes, for example, factory automation. For communication in the functional safety ideology, the IEC 61784 series exists which introduces some common problems and solutions for safe communication. [39]

When the communication channel is not designed and validated to meet the IEC 61508 standards, the channel is a so-called "black channel". On the black channel principle, it is assumed that the channel itself does not detect all possible errors and therefore a dedicated safety communication layer must to be implemented at the top of the OSI model. The principle is shown in figure 3.2. [32]

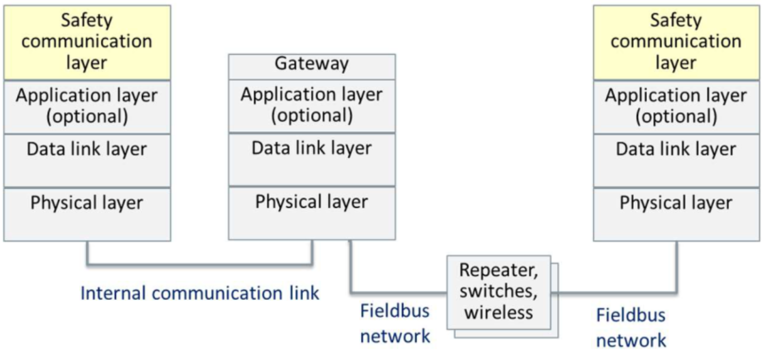


***Figure 3.2.** Safety communication layer principle [32].*

Opposite the black channel is a white channel of communication. On the white channel, every hardware component on the channel is known and they are designed to meet the set safety requirements. Also, all the software included in the system is safety certified. The method of using the white channel is traditionally used in, for example, in the rail industry and has been proven to be very successful. The downside of the white channel is slow migration to newer systems and high development costs. [10]

The standard IEC 61784 [9] defines the following errors possible on the unknown (thus black channel) communication channels:

- Data corruption
- Unintended packet repetition
- Incorrect packet sequence
- Loss of communication
- Unacceptable delay
- Insertion of extra information
- Masquerade
- Addressing.

The following correcting measures are again defined in the IEC 61784 [9] for tackling the possible errors:

- Sequence numbering
- Time stamps
- Time expectations
- Connection authentication
- Feedback message
- Data integrity assurance
- Redundancy with cross-check.

To provide safe communication over the black channel network, several commercial protocols exist. Some examples are protocols such as PROFIsafe, FF-SIS and SafetyNet [34]. The basic principles of the protocols are quite similar and are based on the techniques defined in IEC 61508 standards.

PROFIsafe is the most widely known, so it is used here as an example. The PROFIsafe is an addition to existing PROFIbus and PROFInet technologies that are developed by PI company. The POFIbus is an older fieldbus technology where the messages are transmitted on dedicated PROFIbus wires while the PROFInet is a protocol running on top of an ethernet network. The PROFISafe is defined in IEC 61784 standards and can be used officially on top of the PROFIbus or PROFInet. Its use on top of another protocol is also possible but not officially supported by PROFIsafe profiles [1]. The PROFIsafe meets the requirements to be used up to in SIL 3 applications [39].

The PROFIsafe is a software implementation on top of the PROFIbus or PROFInet networks and is also approved to be used on wireless networks [39]. In PROFIsafe terminology, the nodes exchanging the messages are called F-Host or safety controller and F-Device or safety device [39]. The overall structure of PROFIsafe can be seen in figure 3.3.

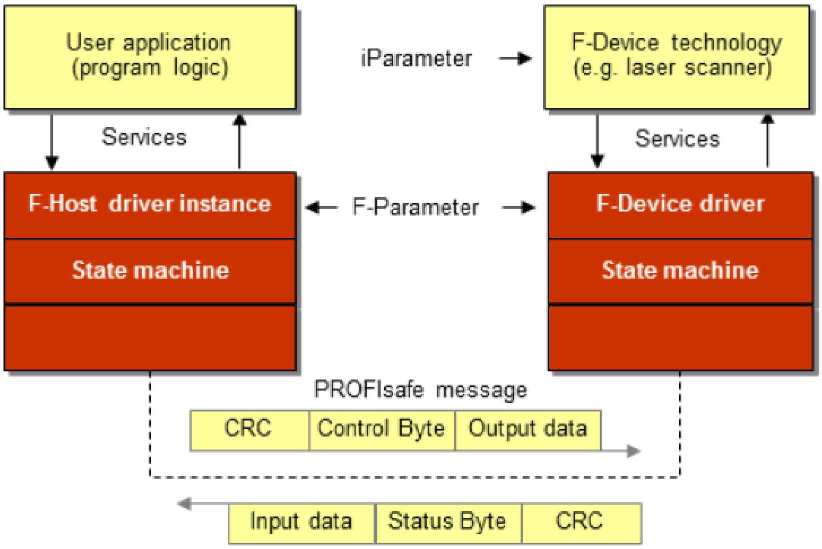


***Figure 3.3.** PROFIsafe system structure [39].*

To handle the error situations defined in IEC 61784 and listed above, PROFIsafe uses the following technical features. For data corruption and insertion of extra information, a 32-bit long Cyclic Redundancy Check (CRC) is used. For unintended packet repetition and incorrect packet sequence, 32-bit long PROFIsafe message numbering is used. To handle the loss of communication and unacceptable delay, time expectations with acknowledgements are used. Finally, for masquerade and addressing, authentication is used between the sender and receiver, using the term codename in PROFIsafe terminology. F-Devices has a timer called watchdog which is restarted in every packet reception. If the watchdog timer expires, the machine goes to a safe state, for example, stop. [39]

The PROFIsafe packet consists of three fields, shown in figure 3.3. The output/input data field, regarding the direction from F-Host to F-Device or vice versa, can carry a maximum of 123 bytes of data. The carried data types are defined in the proprietary General Station Description (GSD) file in every F-Device. The minimum required data length support in F-host is 12 or 13 bytes, depending is it input- or output data. The second field is a control byte or status byte, regarding whether is it the packet sent by F-Host or F-Device. It is used for synchronization of the F-Host and F-Device internal monitoring number generators. The monitoring number generators are used for generating the monitoring numbers for packet numbering. However, the packet numbers are not sent on the PROFIsafe message as their own field, but as embedded in the CRC. The third field of the packet is the 32-bit long CRC. [39]

Using a functional safety protocol on top of the network stack does not primarily set requirements for the underlying network performance. However, because the parameters on the functional safety protocols are configurable if the underlying network technology can provide for example low latency and high reliability, the parameters on the functional safety protocol can be scaled tighter which on the application layer shows as a faster response rate and for example as shorter stopping distance and higher vehicle speeds.

In conclusion, communication in functional safety areas is strictly standardized. It denotes that the structures meeting the functional safety requirements are strictly defined already. This might lead to some extra challenges when implementing new applications requiring functional safety principles with new network technologies. On the other hand, the good thing is that existing protocols exist and can be used to meet functional safety requirements.

4. DECT-2020 AS AN ENABLER

In this thesis, DECT-2020 is investigated as a possible enabler to meet the set requirements for connectivity in the specified applications. The applications cover multiple use cases with very different requirements for connectivity, so the use cases are separated and the fulfilment of the requirements is investigated on every use case one by one.

In this chapter, the basic idea of fifth-generation networks and DECT-2020 is introduced. The chapter goes through the 5G verticals, Ultra Reliable and Low-latency Communication and DECT-2020 including its basic principles and technology features from the physical layer to the convergence layer. At the end of the chapter, the findings of the DECT-2020 performance based on the published studies found in a literature review are disclosed.

4.1 5G triangle

Wireless communication technologies are developed over time. The first generation of analogue mobile technologies began around the 1980s. These networks were spread into different technologies used in different countries and made possible only limited voice services. [11, p.1].

The second generation of mobile communication can be seen to have emerged in the early 1990s when the first introduction of digital networks began. The main goal was still voice, but the networks also supported limited data services. The Global System for Mobile Communication (GSM) saw a wide spread as a second-generation network technology starting from Europe and then spreading to other parts of the world. Even today, the GSM has comprehensive network coverage in many places. [11, p.1].

The third generation High-Speed Packet Access (HSPA) mobile communication began in the early 2000s with a quick increase in data services enabling wireless Internet access. Following the third generation, the fourth generation networks began around 2010, represented mainly by Long Term Evolution (LTE). The LTE further developed the data services from the third generation, increasing the end-user data rates and lowering the delays. [11, p.2]

The fifth-generation networks started to be under discussion around 2012. The term 5G is not related to one specific network technology, but is meant to include a wider range of services to enable future communication needs. [11, p.3]

When in the earlier network generations the development was primarily focused on increasing end-user data throughput only, on the other hand, 5G introduces the so-called 5G-verticals triangle. The triangle is shown in picture 4.1.

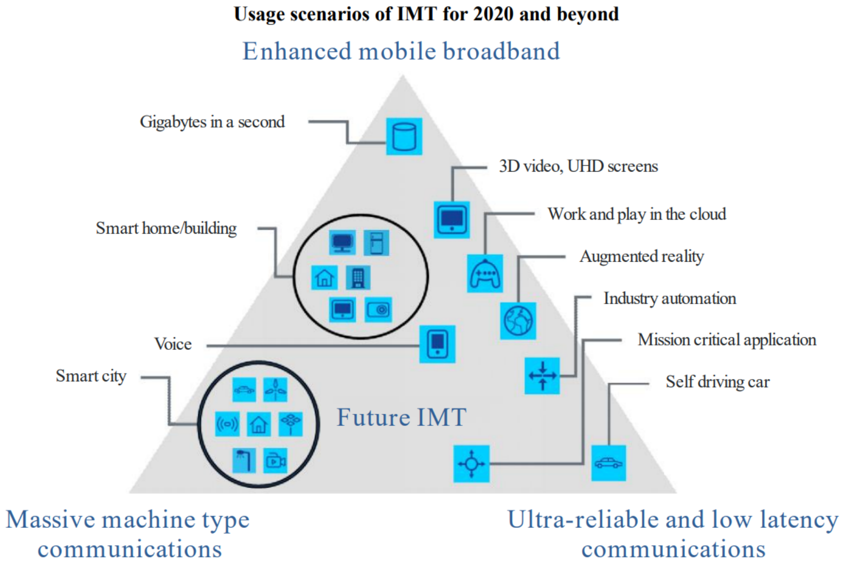


Figure 4.1. *5G verticals [44].*

The development of the 5th generation network is split into three different use case "corners". The classes are enhanced mobile broadband (eMBB), massive machine-type communication (mMTC) and ultra-reliable and low-latency communication (URLLC). The main point of each class is the following:

- eMBB can be seen as a straight evolution of broadband data services for mobile users. It increases the data rates and reduces the latency for data transmission.
- mMTC is meant for use cases which introduce a massive amount of devices in a relatively small area. These systems are, for example, monitoring equipment, sensor and actuators. The usual aspects are that these devices do not need very high data rates but they are considered low-power devices and can be powered by a battery that can last years.
- URLLC is for use cases where extremely high reliability and low latency are required. This class includes examples of traffic safety functions, machine control and industrial automation.

It is still good to comprehend that the three corners of the triangle are the use-case extremes. Many practical use cases are probably none of these directly, but fall between them. From the technology perspective, that forces the technologies to be scalable and not just to be strictly focused on one specific corner of the triangle. [11, p.4]

On technology development, the GSM, HSPA, LTE and 5G NR are all developed by the Third-Generation Partnership Project (3GPP) which is a consortium of seven national Standards Developing Organizations (SDOs) from Europe, Japan, the United States, China, Korea and India. The requirements for the communication technologies are composed by ITU-R, which is the Radio communication sector of the International Telecommunication Union (ITU). The ITU-R defines the spectrum usage for different services in which a subset is identified as International Mobile Telecommunications (IMT) systems. The IMT-2020 standard focuses on fifth-generation wireless technologies and defines the minimum technical requirements for radio interface, evaluation guidelines evaluating the requirements and submission template submitting a candidate template to the evaluation. [11]

4.2 Ultra Reliable and Low Latency Communication

Most of the defined application requirements defined in tables 3.1-3.4 belong in the URLLC corner of the 5G triangle. As stated previously, the use cases are still not tightly in that corner but are spread towards both mMTC and eMMB corners, depending on the actual use case. The main focus is still centralized in the URLLC area.

The URLLC stands for Ultra-Reliable and Low-Latency Communication. Thinking of the name, the term can be divided into Ultra-low Latency and Ultra-Reliable aspects which both need to be fulfilled to fully accomplish the corner. As both aspects are challenging to fulfil it is very challenging to fulfil both at the same time.

The 3rd Generation Partnership Project (3GPP) has set two requirements categories for URLLC communication. The more reliability-oriented requirement set $1 - 10^5$ (99.999 %) connection reliability with layer 2 latency maximum of 1 ms with a 32-byte long packet. The second requirement with more orientation to low latency sets a maximum of average 0.5 ms layer 2 latency on both uplink and downlink. As a note, the 3GPP requirements do not define end-to-end latencies or end-to-end reliability values, so those are left for the application to handle. [14][38] The URLLC requirements set by IMT-2020 is shown in table 4.1.

Table 4.1. *IMT-2020 URLLC requirements [40].*

User plane latency	1 ms
Control plane latency	20 ms (10 ms encouraged)
Reliability	$1 - 10^5$
Mobility interruption time	0 ms

Latency can be defined differently in different situations. The most simple definition of latency is a packet transmission from a given protocol layer to the receiver's corresponding protocol layer. On some applications, such as remote control, the delay occurring from the control signal and feedback coming back, thus round-trip delay could be more interesting. [38]

Even when the Ultra-Low Latency and Ultra-Reliable terms can be divided, they have a connection between them. Petar Popovski et. al. has introduced an idea of a correlation between latency and reliability in the whitepaper Wireless Access in Ultra-Reliable Low-Latency Communication (URLLC) [38] shown in the figure 4.2. The principle states that if we omit the latency requirement between transmitter and receiver (thus latency can be infinite) and we send packets at a packet rate under the channel maximum throughput we get perfect reliability. From the application perspective, we can define a deadline of the maximum allowed latency. Then we can define the probability that latency does not exceed that deadline as reliability and as an outage when it does. The blue curve then shows the probability of transmitted packets within the deadline. [38]

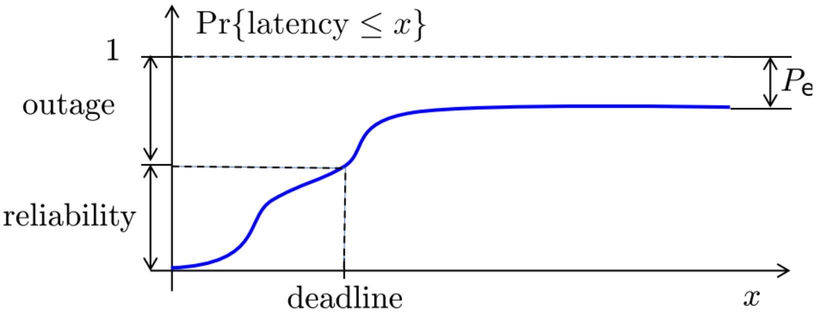


Figure 4.2. *Correlation between latency and reliability [38].*

In the figure, P_e corresponds to the probability of packet loss. It can be seen that in certain situations some packets never reach their destination, for example, due to the end of HARQ retransmission amount, overflow on buffers or synchronization errors. [38]

Based on that theorem, reliability and latency are connected. For example, if some technical improvements are used to lower the latency then the blue curve has a steeper rise which increases the reliability. The same works the other way, if the reliability is increased using some technical improvements, the whole blue curve will be shifted up and then the required reliability level will be reached at a lower latency level. [38]

End-to-end latency is the sum of latency occurring in the different states of the transmission. The majority of the latency occurs on protocol stack, physical signal processing, medium access, actual transmission and propagation delays. The delays in processing can be affected by the design of the use decoder and encoder and their complexity. In radio propagation, the things set by the physical layer and medium access are the core end-to-end latency contributors. [28]

The question is what is enabling Ultra-High Reliability? On the physical layer, diversity is a major role for achieving high reliability. Diversity can be achieved in three dimensions: time, frequency and space. When considering low-latency applications, time diversity is not considered a viable option, but frequency and space diversity can be utilized. [28]

Some technical solutions have been developed to attend to improve the low latency. One is shortening Transmission Time Interval (TTI). The Transmission Time Interval is the time interval when a new packet is sent in the physical layer and thus is the interval when packets are delivered between the physical layer and the upper layer. On OFDM systems the physical layer parameters set the physical layer delay and constitute the base of TTI. On modern communication systems, like 5G NR, the physical layer parameters are scalable, which also offers configurations for short TTI use cases. [37]

The second technical improvement is fast HARQ Retransmission. For the HARQ delay, most of it happens due to the receiver processing of coding, OFDM processing and equalization. Typically, on the LTE, 60 % of processing time is used in turbo decoding. In a discussion, a solution is proposed to use lighter coding schemes that are less resource expensive to decode, but it is not a perfect solution as the coding robustness suffers. The second option is to use prediction on the decoding phase and predict whether the decoding will be successful or not, which provides the HARQ feedback sent immediately after the failed decoding result is evaluated. In this solution, false positives and negatives are an issue. [37]

4.3 Mesh-networking

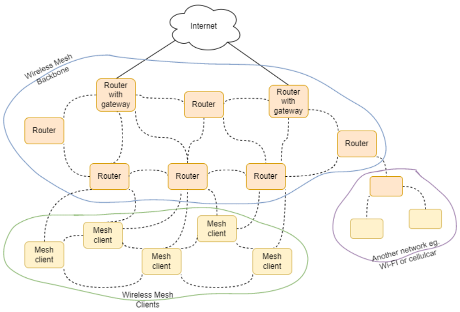
In a mesh network, the network consists of nodes that can operate not only as hosts but also as routers that can forward packets to nodes that are not directly under the coverage of the transmitter node's wireless transmission range. The nodes are establishing the mesh network and maintain it automatically, which keeps mesh networks self-organized and self-configured. [2]

The mesh networks, and multi-hop networks in general, can improve the system performance and reliability compared to point-to-point networks. The system performance is increased due to the need for lower transit power between the links and the coverage extension is done by utilizing more hops. [42]

The mesh network includes two types of nodes: mesh routers and mesh clients. The mesh routers include more features than conventional routers to provide mesh functionalities. The routers have to support the additional mesh routing functions and usually consist of multiple wireless interfaces to either the same or different radio technologies. Usually, mesh clients can also route packets and often include a limited amount of router functions, but they do not offer, for example, bridge or gateway functions to other networks. [2]

The mesh networks can be divided into three groups based on their network architecture [2]. The three types are shown in figure 4.3.

(a) *Backbone mesh network* ***(b)*** *Client mesh network*



(c) *Hybrid mesh network*

Figure 4.3. *Different mesh network types, adapted from [2].*

Backbone mesh network architecture is shown in figure 4.3a. The architecture consists of mesh routers that construct a backbone where other networks can connect. The mesh routers form self-constructing and self-healing links between themselves with one or more gateways to the internet. The other connecting networks can be different in technology than the mesh routers. This architecture is widely used and can be used, for example, to deliver connectivity to neighbourhoods where mesh routers are located at the top of each building, and deliver the connection to the houses' local network. [2]

The second architecture type shown in figure 4.3b is the client mesh network. In that network type, the clients are forming the entire network providing peer-to-peer access between themselves. As the mesh routers are not part of the network, the peers also have to manage functions like routing and self-configuration. [2]

The third network architecture is hybrid mesh shown in figure 4.3c. The hybrid mesh includes the mesh router backbone, which might include connection to other networks. The backbone has a connection from a mesh client network, where clients can access the network via the backbone or directly to each other via meshing [2].

As with any other network, routing is a challenge in the mesh networks. The base problem in routing is to find a route between a source and a destination that achieves the best performance. The routing protocols have to follow the *optimality principle*. If there is an optimal path between nodes A and C which goes via node B, then the optimal path between B and C also has to be on the same route. Based on that principle, the optimal paths form a sink tree on the network from all sources to all destinations. In some circumstances, there can exist multiple routes from source to destination achieving the same performance, thus forming multiple sink trees. The basic principle of routing protocols is to find the routes to form a routing path from any source to any destination. [2]

In real networks, the reality is more complicated than just finding routing paths based on sink trees, especially on mesh-type multi-hop wireless networks. There can be changes in the network topology. There exist many reasons for the variance, but some are links between nodes that can go up and down and the topology can change due to the movement of the nodes or nodes leaving and joining the network. Based on the performance target of the routing, routing based only on the network topology might not be a viable option. There can be other metrics between the hops than the hop counts only. For example, if the delay is considered. Including such routing metrics causes complications to the routing, as there can be coupling between the selected routing path with another possible route, and determining the route path has a coupling to physical resource allocation on the network. [2]

4.4 DECT-2020 NR

DECT-2020, also called DECT-2020 NR or DECT-2020 NR+, is a network technology developed by ETSI targeted to local area wireless applications. The technology use cases are not restricted, but one advertised use case is audio applications. The DECT-2020 operates on the same 1.9 GHz licensed frequency band as the classic DECT and it has compatible collision control with the classic DECT, so both can be utilized in the same area. However, there is no more connection between classic DECT and DECT-2020, DECT-2020 being totally new independent technology. [12]

DECT-2020 is developed to reach Industry 4.0 needs for mMTC and URLLC aspects. The technology is targeted at local area networks that can be deployed anywhere without existing infrastructure. [12]

A base idea of DECT-2020 is to offer a powerful mesh networking functionality, but it also supports conventional star and point-to-point topologies [4]. In DECT-terminology, the nodes are called Radio Devices (RD), which can be either in Fixed Termination mode (FT) or Portable Part mode (PT). The RD in FT mode behaves as a base station and is responsible for coordinating the radio resources and RDs in PT mode connect to it. RDs can also function in both FT and PT modes at the same time when operating in part of the mesh network. [15].

The DECT-2020 can be used in many different topology configurations. The most simple topologies are Point-to-point and Point-to-multipoint links, which are designed to be used as cable replacement links between two nodes or between one node to multiple nodes. In these configurations, one RD is in FT mode, which coordinates the radio resources, and other/others are in PT mode which connects to it. [15]

The second topology type is cell topology, similar to those used on cellular networks. In single-cell topology, there exists one RD in FT mode operating as a base station and multiple RDs in PT mode. In multi-cell topology, multiple RDs in FT mode build a fixed network infrastructure, where every FT has its own cell to serve. RDs in PT mode can move from cell to another cell. [15]

In figure 4.4 the point-to-point, point-to-multipoint and cell topologies are illustrated. In the figure, green represents RD in FT mode and yellow RDs in PT mode.

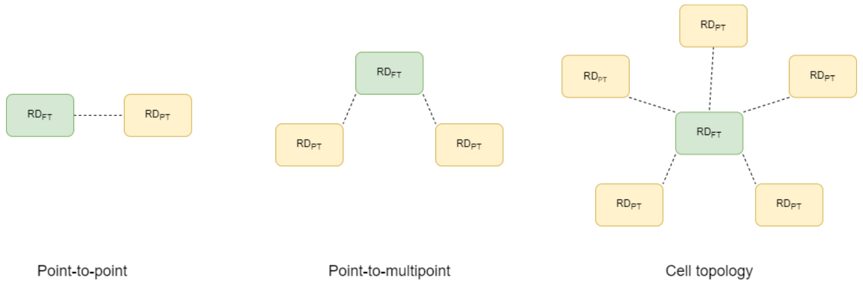


Figure 4.4. *DECT-2020 Point-to-point, point-to-multipoint and cell topologies.*

The third supported topology type is mesh topology. In this topology, the devices can communicate with each other directly or via a hop. The devices can change their mode autonomously depending on the communication context. Each RD can behave as a node transmitting messages, a node forwarding messages from other nodes or a node being the destination of the messages. The devices can communicate directly with other devices or via other devices providing a communication route. Figure 4.5 illustrates a typical DECT-2020 mesh topology formation.

The formation of a mesh cluster works as follows. An RD, which has internet connectivity, starts in FT mode. It selects the used frequencies and begins to send beacons that enable other RDs in PT mode to connect to it. When the other RDs detect the beacons, they can connect to them with the information included on the beacons. The RDs make the decision as to which RD_{FT} or $RD_{FT,PT}$ to connect by themselves. The connecting RD can start behaving as RD_{PT} or in $RD_{FT,PT}$ to start providing connections to other RDs. The RD can change the RD the connection is associated if sufficient. When the RD is connected to another RD it can start sending data. For backend traffic, there is a specified dedicated address for it. [15]

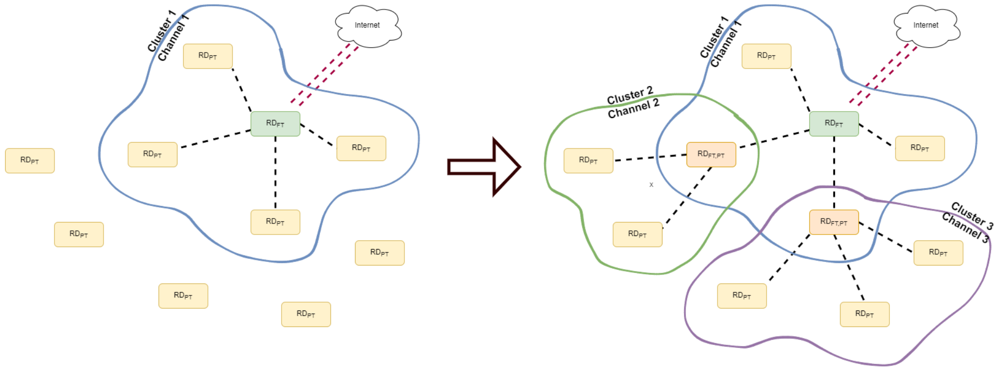


Figure 4.5. *DECT-2020 mesh topology formation, adapted from [30].*

The beaconing procedure is the same on mesh and star topologies. The beacon interval can be adjusted up to seconds to enable low-power applications [15]. On the other end, the beaconing interval can be scaled down to 10ms on more resource-heavy and latency-critical applications [18].

The DECT-2020 mesh systems are scalable to high numbers of devices in the network. The mesh supports autonomous routing, which is based on route cost value, which eliminates the need to maintain a route table on every device. To achieve the required scalability, some of the aspects of the network are [15]:

- All RDs can route data. The routing of the data is based on the autonomous decision of the RD.
- RDs can change their operation mode between FT and PT or be both autonomously.
- The network has no central coordination.
- RDs operating in PT mode coordinate radio resources.
- Multiple RDs in FT mode can be connected to the backend.
- RDs can operate on multiple radio channels.

The DECT-2020 scalability is a clear advantage for the technology. As the network can be configured in many ways to best suit the needs, the features can be finetuned and there is a good chance to get an efficient outcome for the application. The DECT-2020 also supports integration to 3GPP networks using non-3GPP access interworking, which enables DECT-2020 to be connected to the 3GPP network [15].

The DECT-2020 protocol stack consists of four levels: Physical (PHY), Medium Access Control (MAC), Data Link Control (DLC) and Convergence (CVG) layers as shown in the figure 4.6. On top of the DECT-2020 protocol stack, either the application or other protocols, for example, IP can be located.

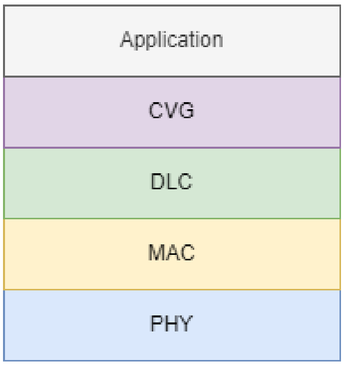


Figure 4.6. *DECT-2020 protocol stack.*

The technical description of the layers is defined in ETSI TS 103 636-1 - ETSI TS 103 636-5 standards. A more accurate description of the protocol layers is described in the following sections.

4.4.1 DECT-2020 Physical layer

The DECT-2020 is designed to supply network deployments in the same area as existing classic DECT and DECT ULE networks. Due to interference management, the networks can be applied on the same frequency and they do not conflict with each other. The DECT-2020 physical layer is designed for operating frequencies below 6 GHz. On the operation of the 1.9 GHz frequency band, the DECT-2020 can operate consistently with classic DECT and DECT Evolution. The 1.9 GHz frequency band is allocated to the DECT in Europe and many other countries. In the USA, Unlicensed Personal Communications Service (UPCS) band is used, albeit it is non-technology exclusive, and still offers versatile clean operation. [12]

The physical layer is the lowest layer on the DECT-2020 stack. The physical layer provides for MAC-layer Physical Control Channel (PCC) and Physical Data Channel (PDC). The physical layer is responsible for the functions, such as symbol modulation and demodulation, frequency and time synchronization, radio characteristics measurements, error detection, HARQ, Multiple-Input and Multiple-Output (MIMO) -processing and beamforming. On request, the information (for example, radio characteristics measurements) are transmitted to the higher layers on the stack. [12]

The RF technology used on DECT-2020 is based on TDD and CP-OFDM. The access schemes utilize both TDMA and FDMA. The resources are divided into separated channels in the frequency domain and separated slots in the time domain. [17]

The supported modulation schemes are BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM and 1024-QAM. Turbo coding is used with supported coding rates of 1/2, 2/3, 3/4 and 5/6. The used modulation and coding rate constructs a Modulation and coding scheme

(MCS) which can be presented as an MCS index. The supported modulation and coding schemes with corresponding MCS index are presented in table 4.2.

Table 4.2. *Modulation and coding schemes [17].*

MCS Index	Modulation	Bits per symbol	R
0	BPSK	1	1/2
1	QPSK	2	1/2
2	QPSK	2	3/4
3	16-QAM	4	1/2
4	16-QAM	4	3/4
5	64-QAM	6	2/3
6	64-QAM	6	3/4
7	64-QAM	6	5/6
8	256-QAM	8	3/4
9	256-QAM	8	5/6
10	1024-QAM	10	3/4
11	1024-QAM	10	5/6

The DECT-2020 transmission is constructed by radio frames with a length of 10 ms. The frame consists of 24 slots with a length of 0,41667 ms which are further divided into 2, 4, 8 or 16 sub-slots. The slot consists of 10, 20, 40 or 80 OFDM-symbols based on the used subcarrier scaling factor μ. The transmission can be done in one slot granularity. For error detection, 16 or 24-bit CRC is used. The DECT-2020 frame structure can be seen in figure 4.7. [17]

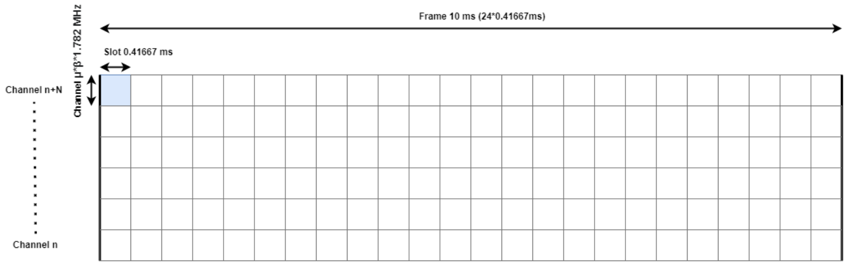


Figure 4.7. *DECT-2020 frame structure, adapted from [17].*

The base channel width is 1.728 MHz which can be aggregated for wider bandwidth from 1,728 MHz to 221,184 MHz. The full table of supported numerologies can be seen in table 4.3. On the table β means for Fourier transforms scaling factor, which is represented to allow varying transmission bandwidths for subcarrier scaling factor μ. B is the total bandwidth including guard bands. N_{DFT} represents the DFT size, N_{CP} cyclic prefix size in samples and N_{OCC} occupied subcarriers including the DC-carrier. The Δ_f^{μ} is subcarrier spacing, T_{symb}^{μ} symbol duration, N_{symb}^{SLOT} number of symbols in one slot and $N_{subslot}^{SLOT}$ number of subslots in one slot. [17]

Table 4.3. *Transmission numerologies, adapted from [17].*

	β	B (kHz)	N_{DFT}	N_{CP}	N_{OCC}
μ = 1	1	1 728	64	8	56
Δ_f^{μ} = 27 kHz	2	3 456	128	16	112
T_{symb}^{μ}= 41.667 us	4	6 912	256	32	224
N_{symb}^{SLOT} = 10	8	13 824	512	64	448
$N_{subslot}^{SLOT}$ = 2	12	20 736	768	96	672
	16	27 648	1024	128	896
μ = 2	1	3 456	64	8	56
Δ_f^{μ} = 54 kHz	2	6 912	128	16	112
T_{symb}^{μ}= 20.833 us	4	13 824	256	32	224
N_{symb}^{SLOT} = 20	8	27 648	512	64	448
$N_{subslot}^{SLOT}$ = 4	12	41 472	768	96	672
	16	55 296	1024	128	896
μ = 4	1	6 912	31	8	56
Δ_f^{μ} = 108 kHz	2	13 824	128	16	112
T_{symb}^{μ}= 10.417 us	4	27 648	256	32	224
N_{symb}^{SLOT} = 40	8	55 296	512	64	448
$N_{subslot}^{SLOT}$ = 8	12	82 944	768	96	672
	16	110 592	1024	128	896
μ = 8	1	13 824	31	8	56
Δ_f^{μ} = 216 kHz	2	27 648	128	16	112
T_{symb}^{μ}= 5.208 us	4	55 296	256	32	224
N_{symb}^{SLOT} = 80	8	110 592	512	64	448
$N_{subslot}^{SLOT}$ = 16	12	165 888	768	96	672
	16	221 184	1024	128	896

The DECT-2020 physical layer packet structure can be seen in figure 4.8. The packet starts at Synchronization Training Field (STF) which follows Data Field (DF). The packet ends at Guard Interval (GI). The STF creates a time domain structure, which is used in the receiver for channel estimation and equalization. [17]

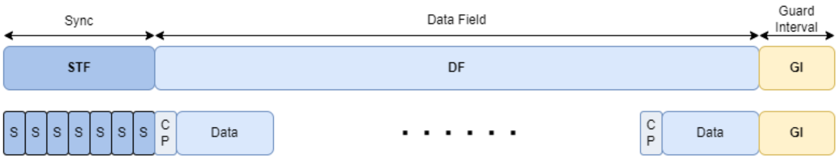


Figure 4.8. *DECT-2020 physical layer packet structure, adapted from [17].*

The Data Field includes Demodulation Reference Signal (DRS), PCC and PDC. The

Guard Interval at the end of the packet reduces overlap at adjacent TDMA timeslots and allows transmission-reception and reception-transmission turnaround. [17]

Depending on the used numerologies and MCS, the DECT-2020 physical layer bitrates can be scaled from 326 kbit/s (1,728 MHz bandwidth with one spatial stream) up to 9 Gbit/s (221 MHz bandwidth with eight spatial streams). [17]

4.4.2 DECT-2020 Medium Access Control layer

DECT-2020's Medium access control (MAC) layer lies on top of the physical layer. The MAC layer is responsible for initiating transmission for paging and broadcast signalling, managing physical layer resources by selecting and accessing channels, logical channel prioritization, mapping packets between logical and transport channels, multiplexing and demultiplexing of MAC Service Data Units (SDU), performing HARQ error correction and integrity protection and ciphering. [18]

The operational principles of the MAC in DECT-2020 can be seen in figure 4.9. In the figure, the solid lines represent the flow for higher-layer data and MAC internal messages to physical channels, and dashed grey lines represent the internal MAC control path [18].

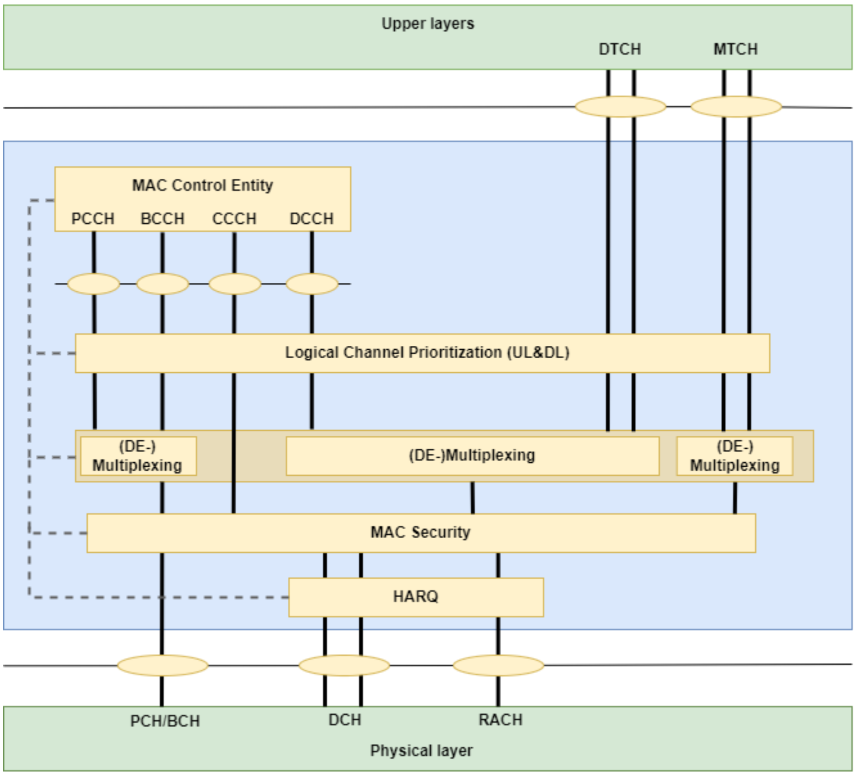


Figure 4.9. *Mac structure overview, adapted from [18].*

The flow of different types of data can be split into channels. The channel is a concept of the flow of information where the channels are separated by the type of information they carry. Two types of channels exist on DECT-2020, logical channels and transport channels. The MAC layer provides the following logical channels to the upper layers [18]:

- Dedicated Traffic Channel (DTCH)
- Multicast (Broadcast) Traffic Channel (MTCH).

Between the Physical layer and MAC layer, the following channels are used [18]:

- Paging and Broadcast Channel (PCH/BCH)
- Dedicated Channel (DCH)
- Random Access Channel (RACH).

Inside the MAC layer, the following channels are used for control information [18]:

- Paging Control Channel (PCCH)
- Broadcast Control Channel (BCCH)
- Common Control Channel (CCCH)
- Dedicated Control Channel (DCCH).

On the DECT-2020 network addressing, there is a 32-bit network ID. From that ID, the 24 Most significant bits (MSB) are used to identify the DECT-2020 network globally and are transmitted on the Cluster Beacon Messages. 8 least significant bits (LSB) of the Network ID are used to identify the network locally, and are generated by the FT corresponding to the radio resources, and are transmitted on the PCC-channel. [30]

On the DECT-2020 devices, there are two different ids. 32-bit Long Radio Device ID (Long RD ID) is used to identify the RD uniquely on the DECT-2020 network. Every RD also has 16 bit Short Radio Device ID (Short RD ID), which is selected randomly by the RD and is used to identify the transmitter and the receiver of the packets in PCC [30]. The Long RD ID is used when initially exchanging Short RD IDs and in situations when the transmitter detects confusion on Short RD IDs [18].

The MAC control entity structure is represented in figure 4.10. The Control Entity includes six functions: Local radio control (LRC), Broadcast control (BCC), Connection configuration control (CCC), Beacon Scanning control (BSC), Random Access control (RAC) and Paging transmission control (PTC).

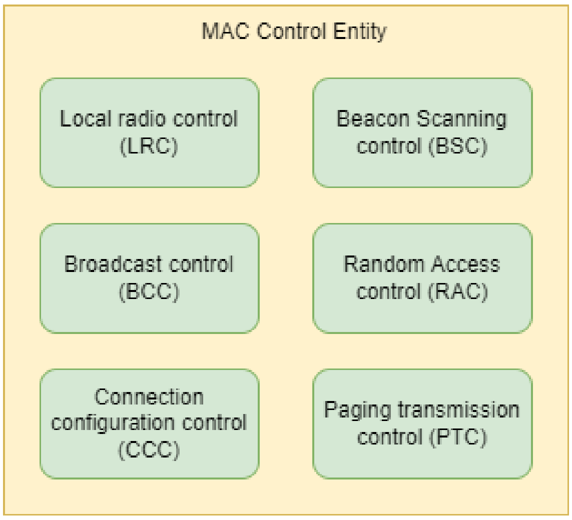


Figure 4.10. *Mac control entity overview, adapted from [18].*

The local radio control function is responsible for radio resources in the local area when the RD is working in FT mode. The broadcast control function is responsible for beacon transmission and other broadcast and multicast transmissions. Connection configuration control is responsible for multiplexing, data mapping to transport channels, handling MCS, HARQ configuration, security of the MAC and handovers with LRC. Beacon Scanning control is responsible for scanning operations. The random access control function is responsible for random access transmission. The paging transmission function is responsible for paging message transmission when the RD operates on FT mode. [18]

4.4.3 DECT-2020 Data Link Control layer and Convergence layer

The Data Link Control (DLC) layer is a layer on top of the MAC layer that provides functions like segmentation and packet routing. The convergence layer provides adaption to the DECT-2020 stack and upper network protocols. The basic full DECT-2020 protocol architecture can be seen in figure 4.13. [19]

The DLC architecture can be seen in figure 4.11. On each radio link between FT and PT or PT and FT, there is a dedicated DLC entity. If the RD is operating in both FT and PT modes simultaneously in mesh networking, there is a dedicated DLC entity for each connection. [19]

The DLC entity can operate in three modes. Type 0 is called transparent mode (DLC-T), type 1 segmentation mode (DLC-S) and type 2 DLC ARQ (DLC-A). [19]

The transparent mode is for simple transparent transmission where the DLC entity has only a transmitter buffer. The DLC entity does not include any other functionalities. The transparent mode adds an octet protocol header. [19]

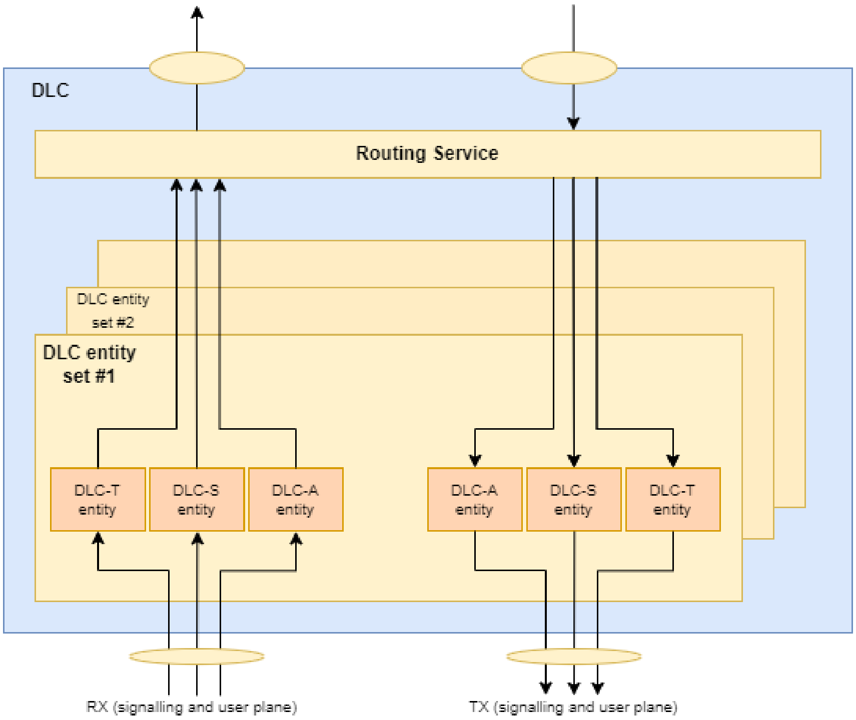


Figure 4.11. *DLC architecture, adapted from [19].*

In the segmentation mode, the DLC entity provides transmission and reception of complete DLC SDUs or segmented DLC SDUs and control of the maximum lifetime of SDUs. [19]

In the ARQ mode, the DLC entity does all the same things as in the segmentation mode but adds the Automatic Repeat Request (ARQ) function. The ARQ interacts with the lower MAC layer HARQ process with Acknowledgement (ACK) and Negative Acknowledgment (NACK) commands. The transmission and reception flow in DLC ARQ mode is depicted in figure 4.12. [19]

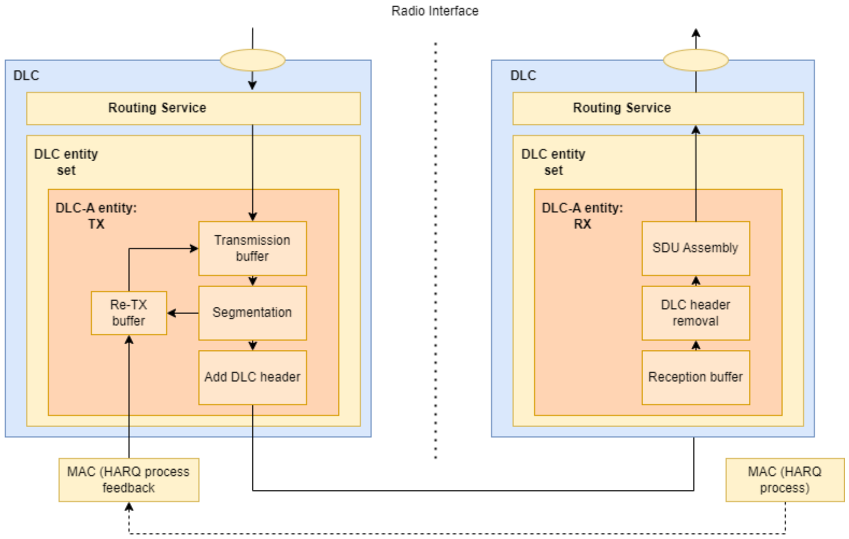
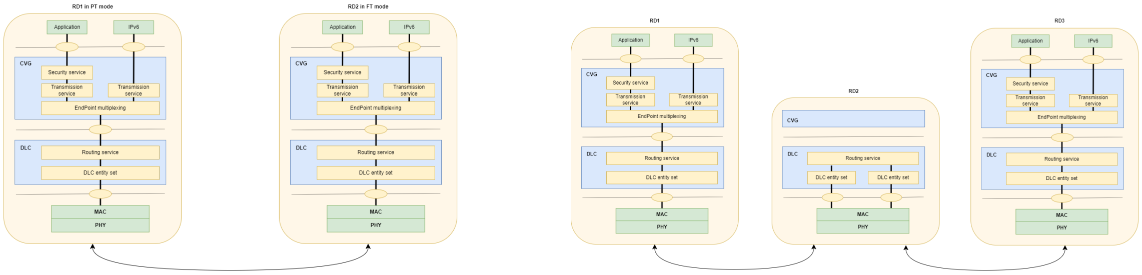


Figure 4.12. *DLC ARQ mode architecture, adapted from [19].*

The overall protocol stack including the MAC layer and CVG layer is depicted in figure 4.13. Figure 4.13a shows architecture with point-to-point or star topology with two nodes, and figure 4.13b with mesh networking.



(a) *Point-to-point*

(b) *Mesh-networking*

Figure 4.13. *Overall protocol architecture on point-to-point and with mesh-routing, adapted from [19].*

In the point-to-point example 4.13a, the RD2 is working in FT mode and RD1 working in PT mode. The backend connection can be connected to the RD2 (not shown in the picture). In the uplink, the data is first processed in RD1 with selected CVG and DLC services prior to sending to RD2 via DECT-2020 physical interface. On the RD2 the data is directed through corresponding DLC and CVG services and transmitted to the application or backend. In the downlink, the logic is similar, but data flows from RD2 to RD1. [19]

The mesh-routing is demonstrated in figure 4.13b. In the example, RD1 is working in PT mode, RD3 in FT mode and RD2 in both PT and FT mode simultaneously. In the uplink example, the RD1 sends data. The data is processed in selected RD1's CVG and DLC layers and sent to RD2 via DECT-2020 physical interface. In the RD2, the data goes up to the DLC routing service, where it is routed to forward to RD3 based on information in the routing header. The data is then sent to RD3 via DECT-2020 physical interface. Finally, in the RD3 the data is processed to corresponding CVG and DLC services and passed to the application or backend (not shown in the figure). On the downlink, the logic is similar, but data flows from RD3 to RD1. [19]

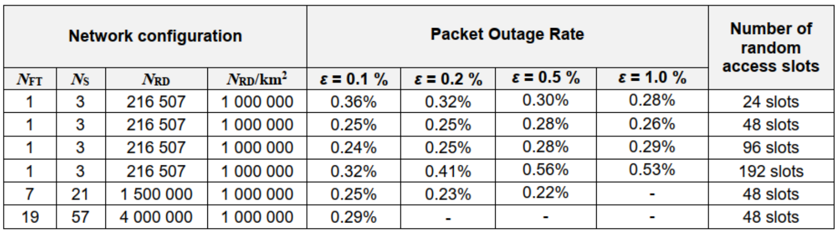
4.5 DECT-2020 performance evaluation from literature

As DECT-2020 is such new technology, just a few pieces of literature are available. In 2020, VTT Technical Research Centre of Finland published a study called "Enabling Massive Machine Type Communications with DECT-2020 Standard" [4]. In the VTT's study, the DECT-2020 mMTC performance is evaluated against IMT-2020 specs using a Network Simulator 3 (NS-3) based simulator tool. In 2021, researchers at Leibniz University Hannover published a study called "Link-Level Performance Evaluation of IMT-2020 Candidate Technology: DECT-2020 New Radio" [33]. In this study, the DECT-2020 URLLC link-level performance is evaluated with IMT-2020 channel models using simulator tools. The third public whitepaper at the time of writing this thesis is Tampere University's researchers published a study called "DECT-2020 New Radio: The Next Step Towards 5G Massive Machine-Type Communications" in 2021 [30]. In that study, DECT-2020 mMTC performance is evaluated using an in-house build WINTERsim discrete-level simulator.

The VTT's study Enabling Massive Machine Type Communications with DECT-2020 Standard focused on the mMTC use case. The model used in the simulation included DECT-2020 physical layer and MAC layer, but no upper layers. The main objectives of the study were to perform an investigation against IMT-2020 requirements of mMTC. The IMT-2020 requirements allow a maximum of 1 % Packet Outage Rate (POR) and a maximum of 10 s packet delay between a source and a destination when the path might include multiple hops and support of device density of 1 million devices per km^2. [4]

VTT's simulations targeted the DECT-2020 mMTC use case with relatively low device throughput. The system architecture imitated typical cellular-type topology, where fixed RDs in FT mode constructed a grid of fixed hexagons. The RDs in PT mode were placed randomly inside the grid. The inter-site distance (ISD), which is the distance between the fixed FDs, was 500 m. The system used 1.728 MHz bandwidth with an MCS index of 1 (QPSK modulation and coding rate of 1/2), 27 kHz subcarrier spacing and a maximum of 8 HARQ retransmission. The system included 1, 7 or 19 RDs in FT mode and 216 k, 1.5 M or 4 M RDs in PT mode. The results are shown in table 4.4. [4]

Table 4.4. *Packet Outage Rate on varying node densities [4].*



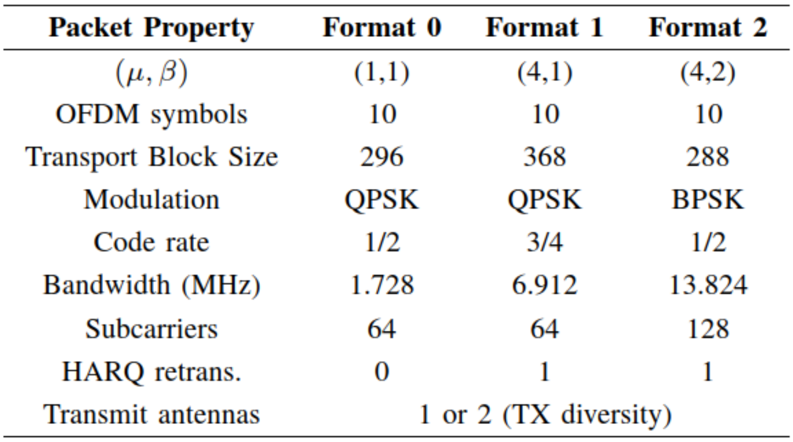
Network configuration				Packet Outage Rate				Number of random access slots
N_{FT}	N_S	N_{RD}	N_{RD}/km²	ε = 0.1 %	ε = 0.2 %	ε = 0.5 %	ε = 1.0 %	
1	3	216 507	1 000 000	0.36%	0.32%	0.30%	0.28%	24 slots
1	3	216 507	1 000 000	0.25%	0.25%	0.28%	0.26%	48 slots
1	3	216 507	1 000 000	0.24%	0.25%	0.28%	0.29%	96 slots
1	3	216 507	1 000 000	0.32%	0.41%	0.56%	0.53%	192 slots
7	21	1 500 000	1 000 000	0.25%	0.23%	0.22%	-	48 slots
19	57	4 000 000	1 000 000	0.29%	-	-	-	48 slots

The simulations show that the DECT-2020 fulfils the IMT-2020 requirements for mMTC of node density and POR. The requirements were met on all simulation configurations, and for example, in a configuration of 4 M RDs in PT mode, the POR was just 0.29 % when the IMT-2020 requirement is 1% with a device density of 1 million. [4]

In the study conducted by Leibniz University Hannover, the DECT-2020 link level performance is evaluated in simulations using channel models provided by ITU-R. Both mMTC and URLLC use cases are considered in the simulations. [33]

The IMT-2020 requires a maximum of 1 ms delay with 99.999 % reliability on at least 32 bytes of transport block size on URLLC. At the beginning of the study, suitable DECT-2020 numerology configurations are found that meet IMT-2020 requirements for URLLC. The same configurations can also be used in mMTC, but for example, the maximum HARQ retransmission amount is more optimised to minimize latency than to maximise the device density. The configurations are listed in table 4.5. As a note, the listed HARQ retransmissions are limited to a maximum of 1 due to the latency requirements, as more retransmissions would exceed the latency budget. [33]

Table 4.5. *Suitable DECT-2020 numerologies for mMTC and URLLC [33].*



Packet Property	**Format 0**	**Format 1**	**Format 2**
(μ, β)	(1,1)	(4,1)	(4,2)
OFDM symbols	10	10	10
Transport Block Size	296	368	288
Modulation	QPSK	QPSK	BPSK
Code rate	1/2	3/4	1/2
Bandwidth (MHz)	1.728	6.912	13.824
Subcarriers	64	64	128
HARQ retrans.	0	1	1
Transmit antennas	1 or 2 (TX diversity)		

In the study's simulation, the system was simulated on a white Gaussian noise channel and the Packet Error Rate (PER) was measured until PER reached 10^{-5} which corresponds to 99.999 %. Firstly, the simulations were done with ten different MCSs.

The packet size was fixed, so increasing the MCS increases the Transport Block Size (TBS). The examined MCSs were 0 to 7 with TBS of 136, 296, 456, 616, 936, 1256, 1416 and 1576 bytes. The simulation results showing the corresponding Packet Error Rate compared to Signal-to-noise ratio (SNR) with different MCS can be seen in figure 4.14. As the whitepaper says, the results are in line with the expectation. With higher MCS, higher SNR is required for achieving the same PER performance. [33]

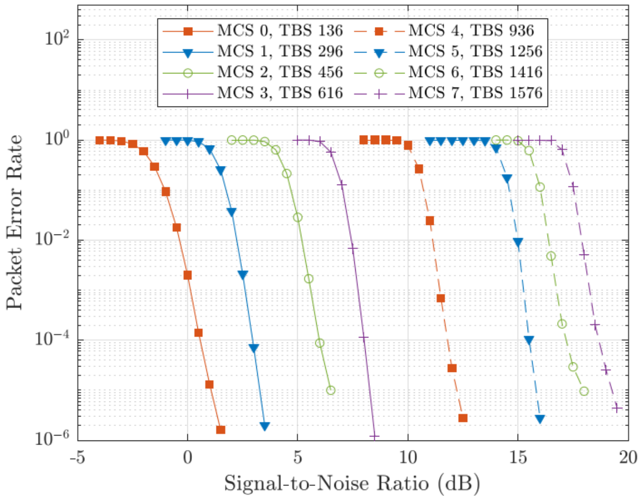
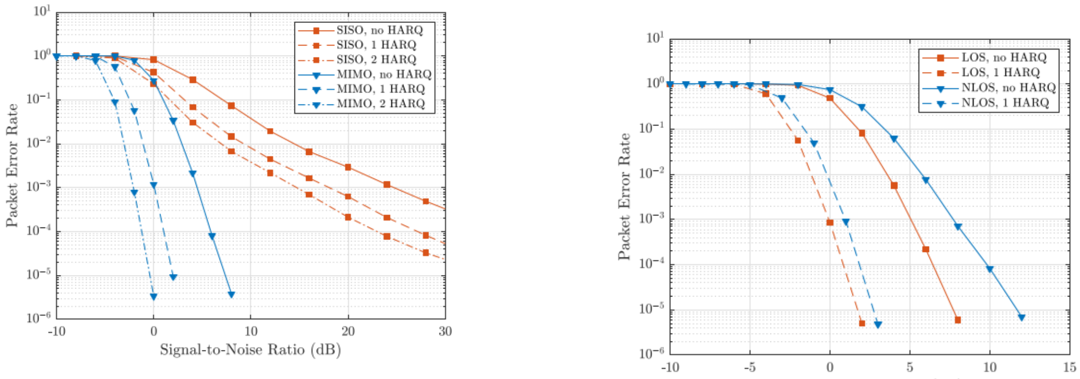


Figure 4.14. *Packet error rate with different SNR values over white Gaussian noise channel with perfect channel knowledge [33].*

In the second simulation, the mMTC-like use case was considered with both Single-Input and Single-Output (SISO) and 2x2 MIMO systems. According to the study, the SISO can be used, for example, in Device-to-device communication when the most simple and affordable solution is required. The results can be seen in the figure 4.15a where a 2x2 MIMO and Line Of Sight scenario, the 10^-5 PER was reached on 7 dB SNR without HARQ retransmissions and in about -0.5 dB SNR with 1 HARQ retransmission. [33]

In the third phase, the URLLC use case was considered by using a Single-Input and Multiple-Outputs (SIMO) system with one transmit antenna and four receiver antennas for maximum reliability. The results can be seen in figure 4.15b. The respective results were 3.5 dB SNR without HARQ retransmission and -2 dB SNR with one HARQ retransmission. [33]



(a) *PER for SISO and 2x2 MIMO with Format 0 configuration on Line-of-sight channel.*

(b) *PER for 1x4 SIMO with different packet formats and different channels.*

Figure 4.15. *Packet error rate with different transmit configurations and channels. [33].*

In the third public study called DECT-2020 New Radio: The Next Step Towards 5G Massive Machine-Type Communications [30] made by Tampere University and Wirepas Oy, the DECT-2020 technological solutions are described and its performance is evaluated and compared to existing Low Power Wide Area Networks (LPWAN) in mMTC use cases with high node densities. The simulations done on the study were conducted by an in-house built Python3-based discrete time simulator called WINTERsim. [30]

In the study's simulations, the DECT-2020 performance is compared to existing technologies. The included competitors are Narrowband Internet of things (NB-IoT) and Long-Term Evolution Machine Type Communication (LTE-M) from 3GPP Release 15 specifications. The used modulation and coding scheme for the DECT-2020 was MCS 3 with QPSK modulation and a coding rate of 3/4. [30]

In the simulations of the study, the Packet Loss Rate and latency are measured compared to the node density in both single-hop mode and multi-hop mesh mode. For environment parameters, the Urban macro model, the Urban micro model and the Indoor office models are used from ITU. [30]

The simulation results can be seen in the figures in 4.16. In the figures, the x-axis is RD node density, measured in million devices per square kilometre. On the left figure of 4.16 the y-axis is Packet Loss Rate (PLR) and on the right figure, latency 99 % percentile is measured in milliseconds. In both figures, the simulations are done by giving the nodes either one channel or three channels of space to operate, marked with a solid line and dashed line respectively. The b-parameter on the figures declares the receiver sensitivity bias level. For example, the notation of B=3 dB means that the receiver works 3 dB above its sensitivity. Changing the bias level higher forces the nodes to connect to the closest node possible. [30]

On the left graph of 4.16 the packet loss rate can be seen as a function of node density. As can be seen, using a multi-hop configuration in mesh produces benefits compared to the single-hop. Increasing available channels from 1 to 3 does not increase the performance dramatically, as the RD is allowed to use only one channel at a time. [30]

On the right graph of 4.16 the delays can be seen as a function of node density. The interesting part of the graph is the comparison to the competitive technologies. As can be seen from the results, the DECT-2020 performs better in every situation, and the gap stretches even further when the node density increases over about 1 million nodes. At about half a million nodes, the DECT-2020 has a delay of 3-7 ms when compared to LTE-M and NB-IoT, where the delays are about 150 ms and 1100 ms respectively. [30]

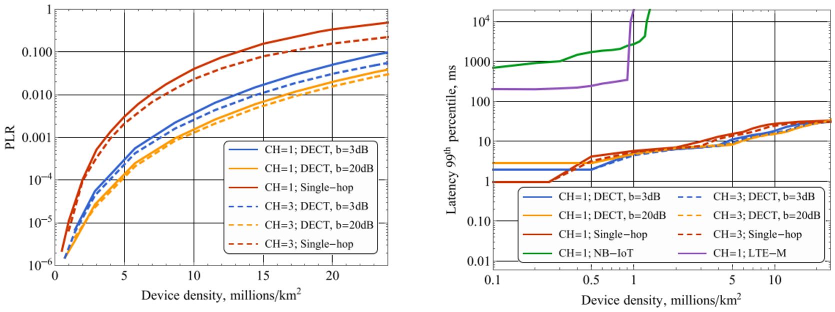


Figure 4.16. *Packet loss rate and latency compared to node density in DECT-2020, BB-IoT and LTE-M [30].*

In conclusion, some existing studies about DECT-2020 performance exist. Studies are mainly theoretical whitepapers including simulations of the DECT-2020 performance. The focus of the studies is focused majority on the mMTC use cases but some analysis of URLLC performance is also conducted. The result from the studies' simulations shows that DECT-2020 has a good performance in high node density scenarios and provides high reliability with a low Packet Error Rate. DECT-2020 also shows a good performance in low-latency scenarios.

5. FIELD TESTS

Satel received a preproduction stage DECT-2020 hardware and software for an early investigation and performance measurements of DECT-2020. The units were preproduction models mentioned for early testing and RD. The development of the hardware and software was still active and the implementation was not yet ready for commercial markets.

The measurements were done on the scale that the hardware offered. Due to hardware limitations, the parameters measured did not cover high-level functionalities of the DECT-2020 technology, but only basic physical layer measurements. From an application perspective, the hardware and software did not include any MAC or higher layers functionalities which denotes that the system, for example, does not have HARQ retransmissions or support for mesh functionality.

5.1 Hardware

The supplied units were only capable of a Physical layer of DECT-2020 with some limitations. The hardware did not include a MAC layer so, for example, HARQ retransmission and any mesh functionalities were not supported.

The limitations restricted the possible tests to exclude many mesh-networking functionalities outside the tests, as they are mainly implemented in MAC and DLC layers of the DECT-2020 stack. However, the hardware provided the possibility to test physical packet propagation, RSSI-2, SNR and PER measurements. The supported MCS numerologies by the hardware are listed in table 5.1.

Table 5.1. *Test hardware supported MCS indexes.*

MCS	Modulation	R	Supported TBS sizes
0	BPSK	1/2	136 - 1992
1	QPSK	1/2	32 - 3960
2	QPSK	3/4	56 - 5536
3	16-QAM	1/2	88 - 5280
4	16-QAM	3/4	144 - 5600

The hardware unit boards consist of an ARM-based CPU and a dedicated modem chip running with DECT-2020 modem software. The modem software is property of the manufacturer and is delivered as a binary, while the application software running on the CPU can be customized by the needs. The application software is written in C and communicates with the modem with an onboard communication bus. The application used on the tests was a simple packet generator. The transmitter generates packets with a running index number as a payload. At the receiver, the packets are received and the payload index number is used as a reference to whether the received packet is consequent of the previous one or if there is a packet or packets missing between the received packets. The results of the reception are printed to Universal Asynchronous Receiver Transmitter (UART), a serial interface where a PC is used to capture the text output. From the UART interface, the received packets RSSI-2, SNR and PER values can be recorded.

5.2 Test plan

Before the field tests a test plan was prepared. The test plan included two sets of tests.

5.2.1 Test 1: TX Power measurement

On the used preproduction hardware, the transmit power can be adjusted in steps described in the DECT-2020 MAC specification [17]. The transmit power can be adjusted by bits in Transmit power field on the Physical Layer Control Field MAC header. The available power levels are from -40 dBm to 32 dBm. Due to the limitations of the hardware, the maximum output power of the used preproduction hardware is +19 dBm declared by the manufacturer. [18]

On the first test, the actual output power was determined by measuring with a spectrum analyzer. The power was measured from the cable connector just before the antenna but without taking into consideration the antenna gain.

5.2.2 Test 2: MCS & RSSI-2 & SNR & Throughput test

On the second test, the actual field tests were conducted. During this test, the RSSI-2 and SNR values were measured and performance was evaluated compared to the distance between the transmitter and the receiver.

In preparation for the test, the transmitter was set on top of a tripod and powered by an external power bank. During the measurements, the transmitter power was set to the maximum available, which was measured in the previous phase. Two interesting MCS values were selected and one was set active by a time to the transmitter. The receiver was set on top of another tripod and powered by a laptop, which was also used for UART recording. The antennas on both ends were omnidirectional.

The transmitter was set in a fixed position and the receiver was moved in 50 m steps. The received RSSI-2, SNR and PER values were recorded. The measurements continued until the signal was too weak to produce sufficient PER. The tests were repeated with a 1.8 m tripod height and a 4 m tripod height. The first simulates equipment operated at the height of the operator personnel, i.e. a handheld device, and the latter simulates use in machinery where the antenna is located on top of the machine's cabin.

5.3 Test setup

The illustration of the test setup is shown in figure 5.1. The setup consisted of two units running with preproduction DECT-2020 firmware. Both units had an external antenna providing 2 dBi antenna gain. One of the units was set as the transmitter and the other as the receiver. On the transmitter side, the power was delivered by an external power bank, while on the receiver side, the receiver was powered by the connected laptop. The laptop was used to record the output data of the received RSSI-2, SNR and PER values for later review.

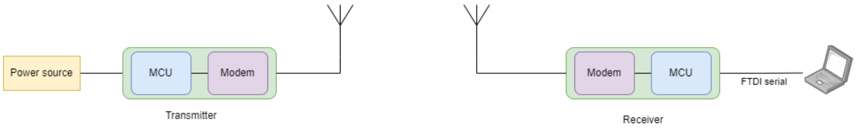


Figure 5.1. *DECT-2020 test setup for measurements.*

The transmitter and the receiver were set up on tripods as declared in the Test plan section. The physical installation of the transmitter is shown in figure 5.2:

Figure 5.2. *Transmitter installation.*

The tests were conducted in an open area providing about 1000 m of line-of-sight propagation. Beyond that, some terrain and trees were present. During the tests, the weather was sunny.

5.4 Tests

From the TX power measurement test, the result shown in table 5.2 was measured. The radiated power was +1 dBm higher than the set +19 dBm in the software, being +20 dBm in total.

Table 5.2. *TX Power measurement.*

Set	+19 dBm
Measured	+20 dBm

The physical layer properties used in the tests are shown in table 5.3. The used carrier frequency was set to meet the EU allocation for DECT. In the tests, carrier aggregation was not used, producing 1.728 MHz bandwidth.

Table 5.3. *Radio properties used in the tests.*

Frequency	1892.16 MHz
Bandwidth	1.728 Mhz
Transmit power	+20 dBm
Antenna gain	2 dBi
HARQ retransmissions	No
Transmit antennas	1

From the available MCS indexes, the indexes shown in table 5.4 were selected. The selected MCSs include the lowest possible aiming for reaching the maximum distance and the highest supported by the hardware aiming for maximum throughput.

Table 5.4. *Used MCS indexes.*

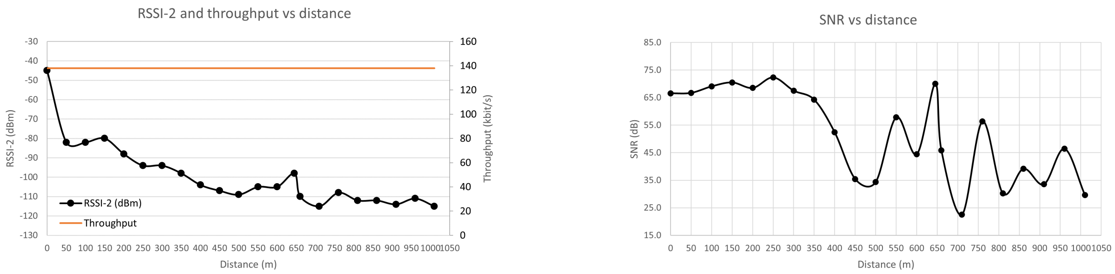
MCS	R	TBS Size (bytes)
0	1/2	136
4	3/4	5600

In tests, the RSSI-2, SNR and throughput tests were tested on MCS 0 with a TBS size of 136 bytes. The receiver was moved in 50 m increments. The antenna height was 1.8 m.

In the higher MCS indexes, the tests included resolving the maximum distance where the reception was possible. The used parameters were MCS 0 with TBS of 136 bytes and MCS 4 with TBS of 5600 bytes. The tests were done on both 1.8 m and 4 m antenna heights.

5.5 Results

The results from the MCS0 test, where the transmitter was moved further in 50 m steps can be seen in figure 5.3. The RSSI-2 levels are shown in figure 5.3a and the SNR levels are shown in figure 5.3b.



(a) *RSSI-2 and throughput vs distance.*

(b) *SNR vs distance.*

Figure 5.3. *RSSI-2 and SNR measurements.*

The RSSI-2 results show quite a steady attenuation to a distance which, is in line with the theory of channel fading. The attenuation increases when the distance becomes longer. At the distance of about 650 m, there was a bridge on the road that was about 1 meter higher than the surroundings, which justifies the elevated RSSI-2 value at the point of 650 m. The measured SNR shows a higher ramping up and down after about 400 m, but it does not seem to correlate directly with RSSI-2 values.

During the testing, it was observed that the connection behaviour from a good connection quality to poor connection quality was very sudden. For some reason, the receiver's modem software froze at the point when the received packets' error rate started to increase. When the freezing occurred, we were not able to get a valid result from the particular test iteration. When the received signal started to be on the limits, getting a valid test required multiple iterations. In figure 5.4 the required iterations of the test to get a valid result are shown.

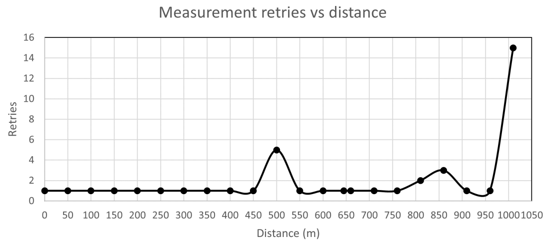


Figure 5.4. *Measurement retries vs distance.*

As can be seen from the figure 5.4, the amount of retries was sufficient until the distance reached around 1000 m. At the point of 1010 m, the successful measurement was got only after the 15th retry.

A similar approach was used when determining the maximum range for other MCSs and antenna heights. The maximum range point was defined at the point where the successful measurement was still acquired with a maximum of a few iterations. The test was done on MCS indexes 0 and 4 and antenna heights of 1.8m and 4m. The results are shown in table 5.5.

Table 5.5. *Maximum transmission distance.*

MCS	TBS (bytes)	Antenna height (m)	Max distance (m)	Throughput (measured)	Throughput (theoretical)
0	136	1.8	1000	138 kbit/s	326 kbit/s
0	136	4.0	1000*	138 kbit/s	326 kbit/s
4	5600	1.8	650	2.2 Mbit/s	13.4 Mbit/s
4	5600	4.0	850	2.2 Mbit/s	13.4 Mbit/s

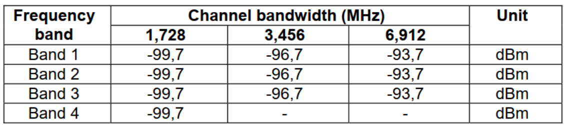
*The test field of about 1000m reached its end.

In table 5.5 the measured throughput is present. Because the MCS index was static, there were no HARQ retransmissions and because of the reception behaviour from good reception to poor reception suddenly, the throughput was almost constant the whole measure period. The measured throughputs were much less than what the ideal maximum theoretical throughput would be. There are many theorems on why the measured throughputs are lower than theoretical ones. The hardware was in a preproduction stage, and based on manufacturers' notes, not ideally optimized for maximum performance yet. The bigger contributing factor is probably the application software used for the tests, as it was not optimized for maximum throughput. For example, a new packet generation started only after the successful transmission of the previous packet and there were no packet buffers where the next packet would have been waiting for the free transmission slot. Also, the software used direct printouts to the UART interface, which was a blocking operation taking a lot of time.

With an MCS index of 0 and antenna height of 4.0 m, the line-of-sight field ends at a distance of around 1000 m. The signal level at this point was good with the RSSI-2 level being -111 dBm. The measurement could have been continued further, but as stated, the field area was limited.

From the DECT-2020 specification [16] the minimum required receiver sensitivity is defined. At 1.728 Mhz bandwidth, the minimum sensitivity is defined to be at least -99.7 dBm shown in the table 5.6.

Table 5.6. *Minimum receiver reference sensitivity requirement [16].*



Frequency band	**Channel bandwidth (MHz)**			**Unit**
	1,728	**3,456**	**6,912**	
Band 1	-99,7	-96,7	-93,7	dBm
Band 2	-99,7	-96,7	-93,7	dBm
Band 3	-99,7	-96,7	-93,7	dBm
Band 4	-99,7	-	-	dBm

The minimum receiver throughput based on the specification is shown in table 5.7. At the 1.728 Mhz bandwidth, the minimum throughput shall be over 112.48 kbit/s. [16]

Table 5.7. *Single receiver minimum throughput requirement [16].*

Parameter	Operating channel bandwidth			Unit
	1,728 MHz	3,456 MHz	6,912 MHz	
Minimum throughout	> 112,48	> 270,56	> 586,72	kbps
Input signal level	-70	-70	-70	dBm/MHz
Propagation condition	static	static	static	

In the measurements, the receiver exceeds both sensitivity and throughput requirements. The receiver was able to work at an RSSI-2 level of -114 dBm and the measured throughput at the MCS 0 was 138 kbit/s.

6. ANALYSIS AND DISCUSSION

The requirements for the set applications on the off-highway vehicles are declared in the tables 3.1-3.5 on the chapter 3. Some interpretations of DECT- 2020 performance against the requirements can be done based on the existing studies and on the conducted field measurements.

The tightest requirement for a latency of 10 ms is set by autonomous remote control use case 3.4. That requirement is less strict than the 1 ms latency requirement from IMT-2020 which is used as a target for URLLC requirements. From the study done by Tampere University [30] the simulated link-level delays are 3-7 ms even when there are 500 000 nodes on the network. Based on that, the DECT-2020 is able to fulfil the set latency requirement set by the applications. It is important to note that the application requirement is the end-to-end latency and the results got from the simulations are from the link level. Even taking this into consideration, that leaves multiple milliseconds of headroom before the 10 ms requirements. If the devices construct a mesh network, the paths include more hops, increasing the end-to-end delay. On the other hand, in mesh networking, the transmitting powers do not need to be that high compared to a cellular type network, which releases bandwidth globally in the area and improves the link-level performance.

From the same Tampere University study [30], the suitability for node densities can be considered. The set requirements for node densities in off-highway vehicles are set to 100 nodes on the area in the use cases 3.1-3.5. Based on the Tampere University study, the DECT-2020 is able to operate with node densities up to millions. Based on that, the DECT-2020 seems to be able to easily fulfil the node density requirement.

The critical requirement for many off-highway vehicle use cases is reliability. The reliability requirement is set in many use cases to 99.9999 %. Based on the simulations done by the Univerity of Hannover [33] the required Packet Error Rate and Bit Error Rate can be achieved in certain radio characteristics, which shows promising performance for DECT-2020. With the conducted field tests, the reliability measurements were not meaningful, as the test setup only involved the physical layer and lacked all the upper layer functionalities, such as ARQ messages.

The application level reliability can be increased by using a dedicated functional safety protocol on the protocol stack. The functional safety protocol offers an extra layer of protection for packet transmission, which can be used to guarantee safe transmission for safety-critical applications if the reliability on the lower levels of the network stack is not guaranteed. The functional safety protocol itself might not need for example very low latency from the network. However, because the DECT-2020 is able to provide a reliable and low-latency connection, the functional safety protocols can also be scaled tighter, which on the application level makes possible, for example, faster response times which then can show as higher vehicle speeds and shorter stopping distances.

The required throughputs vary from under 2 Mbit/s to 100 Mbit/s in the requirements tables 3.1-3.5. In the field tests with limited preproduction hardware, a throughput of 2.2 Mbit/s was measured. The measured throughput exceeds the lowest requirement and is good compared to the development state of the used devices. The 2 Mbit/s throughput already enables many practical use cases, for example, highly compressed video data, automation control data and process data transmission. With the same MCSs, the theoretical throughput should be 13.4 Mbit/s, which should be possible when the limitations on the preproduction hardware and software are solved. With that throughput level, DECT-2020 start to exceed most of the final use-case requirements for throughput defined in this thesis. It is important to note that the DECT-2020 standard supports even higher MCSs and techniques like multi-antenna transmission, which should enable throughput of up to 9 Gbit/s.

In the requirements 3.1-3.5 the operational area is defined to be a circle with a radius of 1 km. If the network topology is a conventional cell-type topology and there is one base station in the centre of the area, then the maximum link distance would have to be 1 km. On the other hand, if the network consists of nodes forming a mesh, then the distances between nodes are smaller. The actual distances on the mesh network depend on the node count and their location at the moment. The measured maximum achieved range on the field measurements was 1000 m which was achieved with an MCS index of 0 and antenna height of 1.8 m. With an antenna height of 4 m, which simulates the situation when the antennas are located on top of a machine, a range of more than 1000 m would have been measured, but the measurement field was too small. With the higher MCS index of 4 a range of 850 m was measured. The tests show very promising performance compared to the requirements. The requirement of 1000 m link distance is reached with the lower MCS index of 0 and it was very close even with the higher MCS index of 4.

Because the DECT-2020 has a strong development focus on mesh networking, using the mesh functionality would also be a potential candidate for extending the range. When the mesh is used, the individual links between nodes can be shorter and the transmission powers can be lower. It still depends of the application whether a mesh or a conventional point-to-point architecture is better for it.

Based on the existing studies' results and field measurements, there is no possibility to do deductions of fulfilling mobility requirements in practice. More studies are needed to investigate the mobility performance of DECT-2020 technology.

At the current state of DECT-2020 development, the available hardware sets limitations to possible field tests, and the software implementations do not yet cover the full DECT-2020 protocol stack. Currently, the expectation for publicly available DECT-2020 hardware is predicted for the end of the year 2023 based on some manufacturers' announcements [35].

In conclusion, based on the literature review and field tests, the DECT-2020 is a promising technology candidate for industrial off-highway vehicle machine control applications. It uses an interference-free 1.9 GHz spectrum and offers high throughput, support for high node densities and a good range, which is extendable with mesh networking. Still, more investigation is needed for the reliability and mobility aspects of DECT-2020 that were not able to be taken into account in this thesis. Hopefully, the first DECT-2020 capable development units are published by the end of the year 2023 as the manufacturers have scheduled.

7. CONCLUSIONS

In this thesis, the DECT-2020 capabilities are investigated for future connectivity needs of off-highway vehicle machine control applications. The thesis work includes the definition of requirements for certain applications of off-highway vehicles, a quick overview of DECT history and a technical overview of DECT-2020 technology. After the definition of the research question, a literature review of existing DECT-2020 studies is conducted and the research is complemented with field measurements.

At the beginning of the work in chapter two, the history of DECT technology is discussed. The historical part gives the history of classic DECT being an old technology starting from the 1990s which is then updated with NG-DECT, DECT ULE and DECT Evolution. The older DECT technologies form the base of the 1.9 GHz carrier frequency allocation around the word which is used in DECT-2020.

In the third chapter, the research question of off-highway vehicle machine control connectivity challenges is opened. The chapter introduces the current stage of controlling the machines and a brief forecast of what the upcoming changes in the machine control systems will be. At the current time, the machines are driven by operators inside the cabin, and it is predicted that in the future the control is moved to a remotely located control room and fully autonomous operation after that. Based on the future applications, the chapter introduced five use cases and their requirements. The included use cases are Building Information Model -transmission, remote control by humans, remote control autonomously, video feed transmission and safety signalling applications. The requirements include throughput, latency, range, mobility, reliability and the number of data links on the area. The chapter also discusses environments where off-highway vehicles are used and the challenges it introduces to communication due to difficult radio propagation characteristics. At the end of the chapter functional safety is introduced and how dedicated functional safety protocols can be used to reach the required functional safety level.

In the fourth chapter, the technical implementation of DECT-2020 technology is discussed. Before the technical details of DECT-2020, the 5G triangle and mesh networking are discussed. After that, a comprehensive walkthrough of DECT-2020 technology is performed. The DECT-2020 protocol stack consists of physical, MAC, DLC and CVG layers. A high focus on the DECT-2020 technology is efficient mesh networking, but it also supports functions to achieve low latency or high throughput to support many different application needs. The DECT-2020 operates on the same 1.9 GHz frequency range as the classic DECT and can be deployed in the same area coexistent with classic DECT without interference.

In the last section of the fourth chapter, a literature review of existing DECT-2020 studies is conducted. The DECT-2020 technology is so new technology only a few published whitepapers exist during the time of writing this thesis. The three studies from VTT Technical Research Centre of Finland, Leibniz University Hannover and Tampere University is summarized in this chapter and their finding are disclosed. Based on the studies, the DECT-2020 shows good performance on high node density scenarios and provides high reliability with a low Packet Error Rate. DECT-2020 also shows a good performance in low-latency scenarios.

In the second last chapter, self-produced field tests are conducted. For the testing, a preproduction state DECT-2020 hardware and software was used. The hardware had some restrictions and the implemented software stack only included the physical layer with some restrictions. Because of the hardware, software and upper layer restrictions only basic measurements were able to be performed. The measurements were performed with one transmitter and one received with one omnidirectional antenna on both ends. A throughput of 2.2 Mbit/s with MCS 4 and a range of 1000 m with MCS 0 was measured. Theoretically, a throughput of 13.4 Mbit/s can be achieved with the same MCS parameters when the restrictions of the hardware are handled in the final products. First DECT-2020 units are estimated to be available at the end of the year 2023 based on some manufacturers' announcements.

The last chapter included the analysis and discussion would the DECT-2020 fulfil the requirements for off-highway vehicles machine control applications. The analysis is done based on theoretical aspects from DECT-2020 standardization, analysis of published DECT-2020 whitepapers and conducted field tests. Compared to the requirements defined for off-highway remote control applications, the DECT-2020 fulfils the latency and node density requirements. The DECT-2020 shows promising performance on throughput which exceeds the lowest requirements even with preproduction hardware and also exceeds the range requirement of 1000 m. The reliability and mobility aspects of DECT-2020 still need more investigation.

In the final conclusion, the DECT-2020 shows as a promising candidate technology for off-highway vehicles machine control applications. The DECT-2020 reliability and mobility aspect still needs more investigation, but the DECT-2020 shows promising performance in the other requirements areas. Based on the literature review the DECT-2020 should meet the latency and the node density requirements for set off-highway vehicles machine control applications and based on the conducted field tests, the measured range and throughput were close to the requirements and showed very promising performance even on the preproduction stage devices.

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